UNIQUE WORDS FOR IDENTIFICATION AND SYNCHRONIZATION IN TDMA SATELLITE COMMUNICATION SYSTEMS

Philip Myron Sanborn

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THESIS

UNIQUE WORDS FOR IDENTIFICATION AND
SYNCHRONIZATION IN
TDMA SATELLITE COMMUNICATION SYSTEMS

BY

Philip Myron Sanborn

June 1974

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The basic concepts of a satellite communications TDMA system are briefly reviewed, with emphasis on functional receiver requirements. A correlation

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Unique Words for Identification and Synchronization in TDMA Satellite Communication Systems

by

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Lieutenant, United States Navy
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Submitted in partial fufillment of the
requirements for the degree of

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The basic concepts of a satellite communications TDMA system are briefly reviewed, with emphasis on functional receiver requirements. A correlation detection scheme is hypothesized, from which false and miss-detection probability expressions are derived. Criteria are then established for the selection of sequences suitable for use as unique words. Representative unique words of length 15 through 20 are included, along with an explanation of the difficulties encountered in devising an efficient computer search routine.

TABLE OF CONTENTS

I. INTRODUCTION---------- 9

A. TDMA SYSTEM DESCRIPTION---------- 9

1. Receiver Functional Requirements----------10

2. Frame and Burst Format----------11

3. Unique Word Functions----------12

B. DETECTION AND SELECTION OF UNIQUE WORDS-------13

II. DETECTION OF UNIQUE WORDS----------14

A. BASIC DETECTOR DESIGN----------14

B. STEADY-STATE APERTURE GATING----------16

C. ACQUISITION GATING----------19

1. Frame Reference Gating----------20

III. UNIQUE WORD SELECTION CRITERIA----------22

A. LENGTH----------22

B. AUTOCORRELATION CRITERIA----------22

C. CROSS-CORRELATION CRITERIA----------26

IV. PRESENTATION OF RESULTS----------33

A. CHOICE OF DETECTOR APERTURE AND THRESHOLD-----33

B. UNIQUE WORD SYMMETRIES----------35

C. UNIQUE WORD SETS----------36

D. FALSE DETECTION PROBABILITIES----------41

1. Probability of False Detection in the Random Region----------41

2. Cross-Correlation Bound----------42

3. Example System Calculations----------42

V. CONCLUSIONS----------47

APPENDIX A Unique Word Sets----------49

APPENDIX B Determination of Burst Drift Rate----------53

APPENDIX C Detection Probabilities----------56

APPENDIX D Computer Program----------66

LIST OF REFERENCES----------79

INITIAL DISTRIBUTION LIST----------81

LIST OF TABLES

I. Bit Rate Doppler and Maximum Displacement of a Unique Word Over One Frame Period----------19

II. Miss-Detection Probabilities----------34

III. Sets Obtained for h=2----------40

IV. Sets Obtained for h=1 and h=3----------41

LIST OF FIGURES

I. Frame and Burst Format----------12
II. Digital Correlation Detector----------15
III. Autocorrelation Criteria----------24
IV. Cross-Correlation Criteria----------28

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I. INTRODUCTION

The possible use of time-division multiple-access (TDMA) in satellite communications has received a considerable amount of attention in recent years. In a TDMA system, many stations use the same satellite repeater on a time shared basis. Transmitter timing must be synchronized so that only one station's signal accesses the repeater at any given time; and, further, so that successive signal bursts are closely spaced in order to make efficient use of the repeater capacity. Continuously changing ranges from ground stations to the satellite (Appendix B) make transmitter synchronization a non-trivial problem. Once the synchronization problem is solved, TDMA offers several advantages over current frequency-division multiple-access procedures [1,2]. Schmidt [3] outlined the proposed application of TDMA to the INTELSAT-4 series commercial communication satellites.

A. TDMA SYSTEM DESCRIPTION

As each station must transmit in timed bursts, transmissions are necessarily digital and provisions must be made for the sampling (and multiplexing) of the transmitted information channel(s). This process must be timed so that it is in consonance with the burst repetition frequency (BRF) and transmitted data rate. When analog-to-digital conversion is involved, the analog sampling rate must be equal to, or a multiple of, the BRF; a sample storage capability is required when the sampling rate is a multiple of the BRF. When information to be transmitted is in the form of a continuous bit stream, a buffer is required to store a given portion of the bit stream for transmission at the (higher) data transmission rate. In either case, the number of information channels that can be transmitted in a burst of given length is a direct function of the ratio of

transmission rate to information rate. Time-division multiple-access, then, is in effect a higher level form of time-division multiplexing. TDMA is a time sharing at RF, while TDM is a time sharing at baseband, before carrier modulation. The process of several transmitted signals time sharing a satellite repeater is conceptually similar to that of several information channels time sharing the same RF carrier.

Given that transmitted signals are neatly interleaved in their arrival at the satellite, they will be retransmitted in the same fashion and received on the ground without any interference overlap. A receiver must first recognize when a burst is of interest and then, in the case of multiplexed transmissions, select particular information channels within the burst and route them to appropriate end terminals. In order to do so, the receiver must be provided with certain control information.

1. Receiver Functional Requirements

Successive received bursts have been originated by different, in general widely separated, stations whose carrier frequencies are not coherent in frequency and phase. Therefore, prior to the demodulation of each burst, the receiver local oscillator must be locked in frequency and phase to that of the incoming carrier using phase-locked loop techniques. (Use of differential phase-shift keying removes the carrier recovery requirement at the expense of error-rate performance [4].) Similarly, once carrier recovery has been accomplished, the receiver bit timing oscillator (clock) must be synchronized to the incoming bit stream. Bitzer [5] proposed a system design for establishing coherent bit timing among all stations and Suguri, Doi and Metzger [4] reported on the successful test of this type of system. In such a system, receiver and transmitter clocks are continuously adjusted to maintain coherency within acceptable limits, obviating the need for gross adjustments to the receiver clock preparatory to burst demodulation.

With the local oscillator and clock synchronized, demodulation of the incoming signal occurs. Embedded somewhere in the beginning of the burst must be information which the receiver can extract to obtain transmitting station identity, word (channel) synchronization and channel status. Demodulation/demultiplexing of the information channels commences thereafter.

2. Frame and Burst Format

Satellite repeater access time is divided into frames, a frame being the length of time allotted for the transmission of one burst from every station. The frame length is typically 125 usec, or a multiple thereof, to conform to the Nyquist sampling rate for voice (8KHZ) [3,6]. A station is assigned a time slot within the frame for the transmission of its burst, the length of which depends on the anticipated channel requirements. A guard time of typically 200 nsec or less separates the time slots to preclude burst overlap.

Each burst commences with a preamble, followed by the information channels. A typical format is depicted in Fig. 1-1. A fixed pattern of dummy bits is inserted at the beginning for the purpose of locking up the local oscillator and clock. A constant string such as 0000••• for carrier recovery, followed by an alternating pattern such as 1010••• for bit timing recovery is typical. Following the recovery bits is a fixed sequence of bits unique to the transmitting station, the "unique word." More will be said about the unique word below. The remainder of the preamble contains control signals and orderwire transmissions necessary for assignment and control of the information channels.

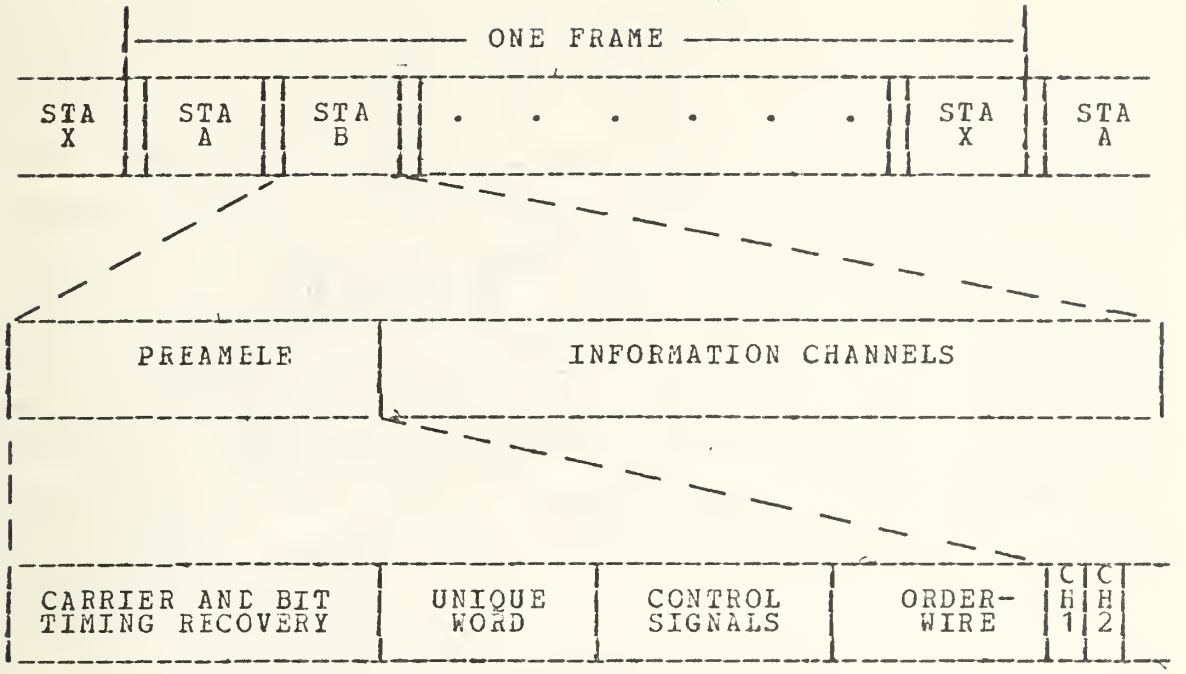

Figure 1-1
Frame and Burst Format

TDMA efficiency is a measure of the total time allotted to the transmission of actual information versus the total available repeater time. The preamble is wasted transmission time in this sense and considerable effort has been expended to reduce its length [4,5,8,9].

3. Unique Word Functions

To the extent that it is recognizable to the receiver, the unique word can be used to identify the originating station. It may also be used as a timing reference to establish word synchronization, resetting a bit counter which properly routes the control and orderwire portions of the preamble and indicates the beginning of the first information channel.

It has been assumed up to this point that all transmitting stations are synchronized so that no burst overlap occurs. Nothing has been said about how synchronization is acquired or maintained. The usual method of doing so is to use the unique words as timing marks

within the frame. One station is designated as the master station and its unique word used as the fundamental timing reference for the frame. All other stations compare the time difference between their own unique word and the reference, as received from the satellite, and adjust transmitter timing as necessary, one bit per frame, to maintain proper separation. This problem of transmitter synchronization is of interest herein only in that the unique word plays a vital role, and will not be further pursued. References 3,7,9 and 10 offer a detailed description of the various factors which must be considered and provide insight as to how a synchronization package might be instrumented.

B. DETECTION AND SELECTION OF UNIQUE WORDS

A TDMA system of the type outlined above can be operated successfully only if the receiver is able to detect the receipt of a unique word and differentiate one from the other. Some type of correlation detector is inferred. Proposed detector design features and operation are presented in Section II. Then, in Section III, criteria are established for the selection of unique words which yield acceptable miss-detection and false detection probabilities.

Interest in the subject was motivated primarily by the discussions of Schrempp and Sekimoto [11]. Much of the detector design philosophy is borrowed from their work, and their approach to unique word selection has been instrumental in obtaining an appreciation for the fundamental requirements which must be considered. The selection criteria set forth in Section III and the subsequent computer search results represent the major products of this research effort.

II. DETECTION OF UNIQUE WORDS

A unique word is a fixed binary sequence of length N. Given a knowledge of the elements of the sequence, detection can be accomplished by comparing received bits, N at a time, with a replica of the sequence stored in the receiver; i.e., by using correlation techniques. The probability of missing the unique word (miss-detection) and the probability of receiving the sequence at random (false detection) are fundamental considerations in the evaluation of detector effectiveness.

A. BASIC DETECTOR DESIGN

A digital correlation detector of the type depicted in Fig. 2-1 is postulated. The element values of the unique word are set semi-permanently in a register and the demodulated bit stream is clocked through the shift register. The corresponding elements of the two registers are added, modulo-2, once each bit period and the results are summed algebraically for input to the threshold network.

The modulo-2 operation is defined by,

$$0 \oplus 0 = 0$$
$$0 \oplus 1 = 1$$
$$1 \oplus 0 = 1$$
$$1 \oplus 1 = 0$$

And the input to the threshold network is,

$$R = \sum_{i=1}^{H} (S_i \oplus U_i) \qquad (2.1)$$

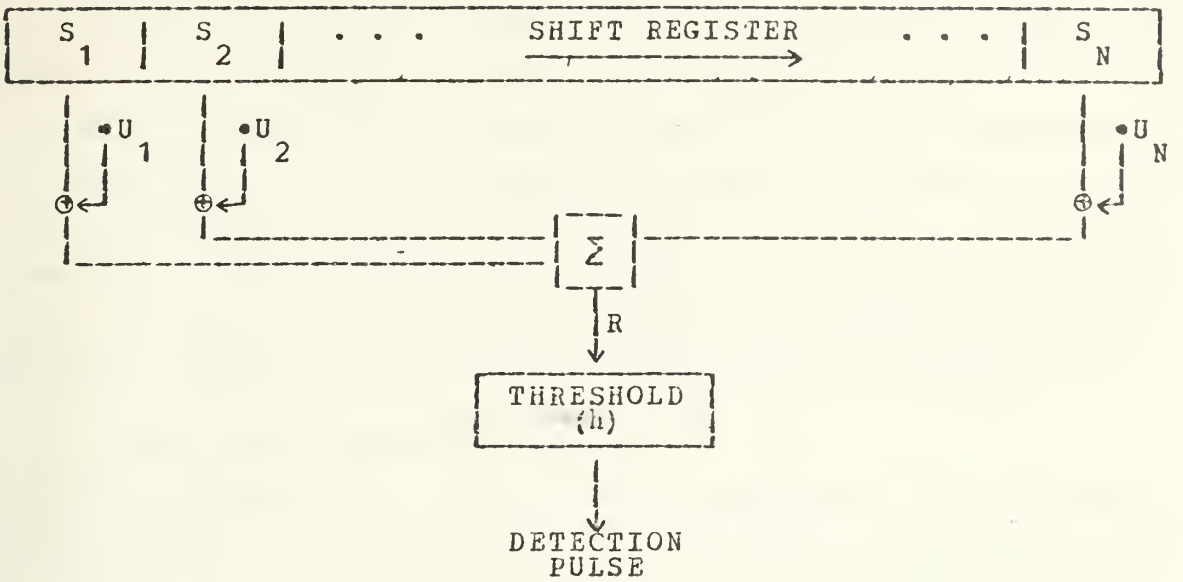

Figure 2-1
Digital Correlation Detector

R therefore equals the number of disagreements between S and U. The threshold network is designed so that a detection pulse is produced whenever there are h or fewer disagreements; that is, whenever $R \leq h$. The setting of a threshold permits the detection of unique words which contain up to h transmission errors and thereby reduces the miss-detection probability. The probability of false detection increases in doing so, however, due to the increased opportunities for a random match-up.

It should be noted that R, as mathmatically defined, is in fact the inverse correlation function of S and U. When the elements of S and U all match, R=0; and when there is complete disagreement, R=N. Alternative detector designs can be envisioned which would produce the true correlation function at R; e.g., construct adders that produce the complement of the modulo-2 sum and design the threshold network so that a pulse is produced whenever $R \geq N-h$. Of course, in the end, the voltage levels associated with '0' and '1' are what determine the actual "value" of R.

Whichever of the various alternatives are chosen, the end result is the same: a detection pulse is produced whenever there are h or fewer disagreements between S and U.

The capability of receiving more than one transmitting station is provided by a parallel bank of detectors, each set to the unique word of one of the transmitting stations. The received bit stream is passed simultaneously through each detector and the resulting detection pulses are used to control receiver functioning, as described in Section I.A.3.

B. STEADY-STATE APERTURE GATING

The probability of false detection is reduced significantly if the detector can be gated so that it begins looking for a unique word just prior to its receipt, and is otherwise inactive. The detection pulse itself may be used to generate such a gating signal under steady-state conditions; that is, once the unique word has been initially acquired.

A unique word is transmitted every T seconds, once each frame, except when a correction is required to maintain proper position within the frame. If corrections are made at the rate of one bit per frame [9,10], the elapsed time between unique word transmissions is bounded by T±b, where b is the period of one bit. The time separation of successive received unique words is further affected by relative motion between the satellite and the respective transmitting and receiving stations. Let d, in bits per second, be the maximum expected doppler induced drift of successive unique word detection pulses. The maximum doppler shift in one frame period is then ±Tbd and the elapsed time between successive receipts of a unique word is bounded by,

$$T_r = T \pm (b + Tbd)$$

$$T_r = T \pm b(1 + Td) \qquad (2.2)$$

This relationship can be expressed in terms of bit periods by dividing through by b. Doing so establishes a limit on the number of bit periods separating successive receipts of a unique word.

$$N_r = T_r/b = T/b \pm (1 + Td)$$

$$N_r = n \pm (1 + Td)$$

where n is the number of bits in one frame.

Defining D as the maximum displacement (in bits) of the unique word from its "periodic" position,

$$D = 1 + Td \tag{2.3}$$

$$N_r = n \pm D \tag{2.4}$$

Upon receipt of a unique word, the detector is turned off, gated back on T-bD seconds later, gated off by the next unique word, etc. False detections can therefore result only from a random match-up within the aperture immediately preceding the unique word.

The question remains as to what to do when the unique word is missed due to errors occurring in transmission. Once the detector is gated on, is it left on until a detection pulse is received (in which case a missed unique word causes an immediate transistion to the acquisition mode); or, is the detector gated off at time T+bD and then gated back on at time 2T-bD, one frame later?[1] In the latter case, how many successive misses are required before cancelling the aperture and reverting to an acquisition mode? The answer depends for the most part on particular

---

[1] It is assumed that the aperture width remains constant and would not be expanded as successive misses occur.

system specifications. When a unique word is missed, all information contained in the burst is lost. Having missed it once, that is having received the unique word with more than h errors, there is a given probability that it will contain more than h errors the next time. Calculation of the probability of a unique word containing more than h errors two or more times in succession is not enough however. The doppler induced burst drift rate must also be considered.

If the drift rate is such that the unique word is received outside the aperture, it will be missed, even if error free. On the other hand, reversion to an acquisition mode may involve a considerable penalty in lost information due to a long average acquisition time. (See Section II.C below.) Thus, a desire to avoid the acquisition mode must be balanced against the diminishing probability (as successive misses occur) of receiving the unique word in the aperture mode. As stated earlier, this is a systems dependent decision, and one that can best be reached empirically in an operational environment. For present purposes, the rather safe assumption will be made that at least two successive misses are required before a transition from the aperture to acquisition mode is effected. A detection pulse turns off the detector and sets a counter which gates the detector on T-bD seconds later. If no detection pulse occurs, the counter turns off the detector at time T+bD. The aperture is of width 2D+1 (bits).

The maximum burst drift which may be expected when using a geosynchronous satellite is computed in Appendix B. Equation B.5 can be substituted into equation 2.3 to obtain values for the maximum displacement of a unique word over one frame period. Table 2-1 contains representative calculated results for the shipboard platform discussed in Appendix B as well as for a platform with a relative velocity on the order of 1000 knots.

v(m/sec)	f(Mbps)	d(bits/sec)	T(msec)	D(bits/frame)
61	1	0.407	0.125	$1+5.1\times10^{-5}$
61	1	0.407	3.0	1.001
61	50	20.3	0.125	1.003
61	50	20.3	3.0	1.06
61	500	203	0.125	1.03
61	500	203	3.0	1.61
2000	1	13.3	0.125	1.002
2000	1	13.3	3.0	1.04

Table 2-1
Bit Rate Doppler(d) and Maximum Displacement(D) of a Unique Word Over One Frame Period for Given Values of Station/Satellite Relative Motion(v), Bit Frequency(f) and Frame Period(T)

C. ACQUISITION GATING

The steady-state operation of a unique word detector was described in the preceding section. Here the process of acquisition is considered. When a receiver is activated, each detector must acquire the associated unique word within the TDMA frame. Likewise, a detector must be switched to the acquisition mode whenever steady-state synchronization is lost. Acquisition, or re-acquisition, may be effected by simply passing the received bit stream through the detector until a detection pulse is received. Then, as in the steady-state mode, the detection pulse switches the detector off and starts an aperture gate counter which in turn switches the detector back on in the next frame. If a second detection pulse is received within the aperture, the detector is transferred to the steady-state mode. Otherwise, the acquisition process continues.

When in the acquisition mode, the bursts of all active stations are being passed continuously through the detector and the probability of false detection is thus relatively

high. Should a false detection occur, a false aperture is set and the next actual unique word detection pulse will be missed. Even when the detection is valid, there is a non-zero probability that the unique word will be missed in the next frame. In either case, acquisition, and transfer to the steady-state mode, is delayed for at least two frame periods. The actual acquisition time may thus span several frame periods.

It is possible to construct a detection pulse storage network which would look at detection pulse locations over two or more frame periods and use majority logic to set an aperture corresponding to the true detection pulse. Although acquisition time would be improved, implementation could prove relatively costly because each detector would require its own network. An alternative is proposed, which makes use of the same aperture network employed in the steady-state mode to gate the detector and reduce the probability of false detection.

1. Frame Reference Gating

Each burst has an assigned position within the TDMA frame. It is known that a particular burst will be received a given number of bits after the receipt of the reference unique work, plus or minus the guard band cushion. The guard band is set so that it prevents burst overlap; that is, it represents the maximum expected displacement of a burst (or unique word) from its nominal position. It is therefore proposed that, during acquisition, the aperture/counter network of a detector be keyed by the receipt of the reference unique word. The aperture is set so that the detector is gated on at the assigned position of the corresponding unique word, minus the number of bits in the guard band, B. If the unique word is missed, the detector is switched off B bits after the nominal unique word position. (The aperture width is 2B+1.) If the unique word is detected, the aperture is set for the next frame. Two consecutive detections key a transfer to the steady-state mode.

In a demand access system, where at least some of the stations are not assigned a permanent time slot, use of frame reference gating is feasible only if all stations can be provided with time slot activation and deactivation information, or can otherwise predict where a given station's burst may appear within the frame. Whether or not it is possible to provide advance activation notification to all stations depends on how a part time station gains access to a time slot. If access is centrally controlled (automatically), then assignment signals from the controlling station can be copied by all stations and used to set the acquisition gate. If a station gains access by seizing a vacant time slot, a receiving station must have other means of predicting where the burst will occur. The results of the computer search for unique words, reported in Section IV, suggest a procedure for meeting this requirement.

For a given unique word length, several different sets are available which have good cross-correlation properties. Unique words from any one set could be assigned to certain stations which collectively have exclusive use of a block of consecutive time slots within the frame. As many such blocks as necessary could be made available to different groups of stations. The number of time slots assigned to each group would be based on collective useage requirements, and could be varied on a scheduled or demand basis. (Demand access implies that the number of time slots would be less than the number of stations.) Those receiver detectors corresponding to the demand access transmitters could then, when in the acquisition mode, be gated on at the beginning of each burst within the demand access sub-frame. The probability of false detection will be somewhat higher than for the single gate procedure proposed above; but, with low cross-correlation between unique words of a set, will be much lower than for "wide open" acquisition.

III. UNIQUE WORD SELECTION CRITERIA

Having outlined the basic detector design concepts, a basis has been formed for the selection of sets of unique words. A detailed analysis of the attendant detection probabilities is presented in Section C. Simply stated, the goal is to find unique words which yield low miss-detection and false detection probabilities. Criteria will be established in this section for doing so.

A. LENGTH

The fewer bits in a unique word, the lower the miss-detection probability. Conversely, the longer the unique word, the lower the false detection probability. The use of a detector threshold and aperture nullifies to some extent the importance of these opposing considerations, but in a gross sense they can never be eliminated as factors influencing the ultimate choice of unique words. In fact, length and the threshold setting are the only parameters available for altering the miss-detection probability.

From the standpoint of efficiency, it is desirable to keep unique words as short as possible. The longer each station's unique word, the less time is available for the transmission of information.

B. AUTOCORRELATION CRITERIA

Operation of the detector in the steady-state mode is described in Section II.B. Loss of channel information will result if (1) the unique word is missed, or (2) a false detection occurs in the aperture prior to the unique word. Either may lead eventually to a drop-sync condition. As (1) and (2) are equally damaging, it would seem appropriate to select unique words in such a way that their combined effect is minimized. Under the conditions described in Section II.B, it is largely a matter of unquantifiable chance

whether a miss-detection or a false detection (within the aperture) is the least desirable occurrence. Accordingly, the following condition was established: if the received unique word contains h or fewer errors, the false detection probability must be zero within the aperture. A false detection pulse will not be produced unless the unique word is going to be missed anyway.

As it is possible for a unique word detection pulse to occur on the last cycle within the aperture, and as the aperture is of width 2D+1, the foregoing condition can be met only if the probability of false detection is zero for the 2D cycles preceding the unique word. This condition can in turn be satisfied only if the autocorrelation function of the unique word is such that,

$$R_j(t) < N - 2h - t \; ; \quad 1 \leq t \leq 2D \qquad (3.1)$$

where t is an integral time variable, the basic unit of which is one bit period, and,

$$R(t) = \sum_{i=1}^{N-t} U(i) \oplus U(i+t)$$

This condition is presented graphically in Fig. 3-1. R(t) is equal to the number of agreements between the (error-free) N-t displaced unique word bits and the detector setting. Up to h errors are permitted in the unique word under the prescribed conditions and it is possible that these errors may be such as to produce additional agreements, giving a total of R(t)+h agreements from the displaced unique word alone. There are t non-unique word bits in the detector. If all of them match with the detector setting, a combined total of R(t)+h+t agreements results. As N-h or more agreements are required to produce a false detection, the probability of such occurrence is zero if R(t)+h+t<N-h, and the validity of inequality 3.1 is established.

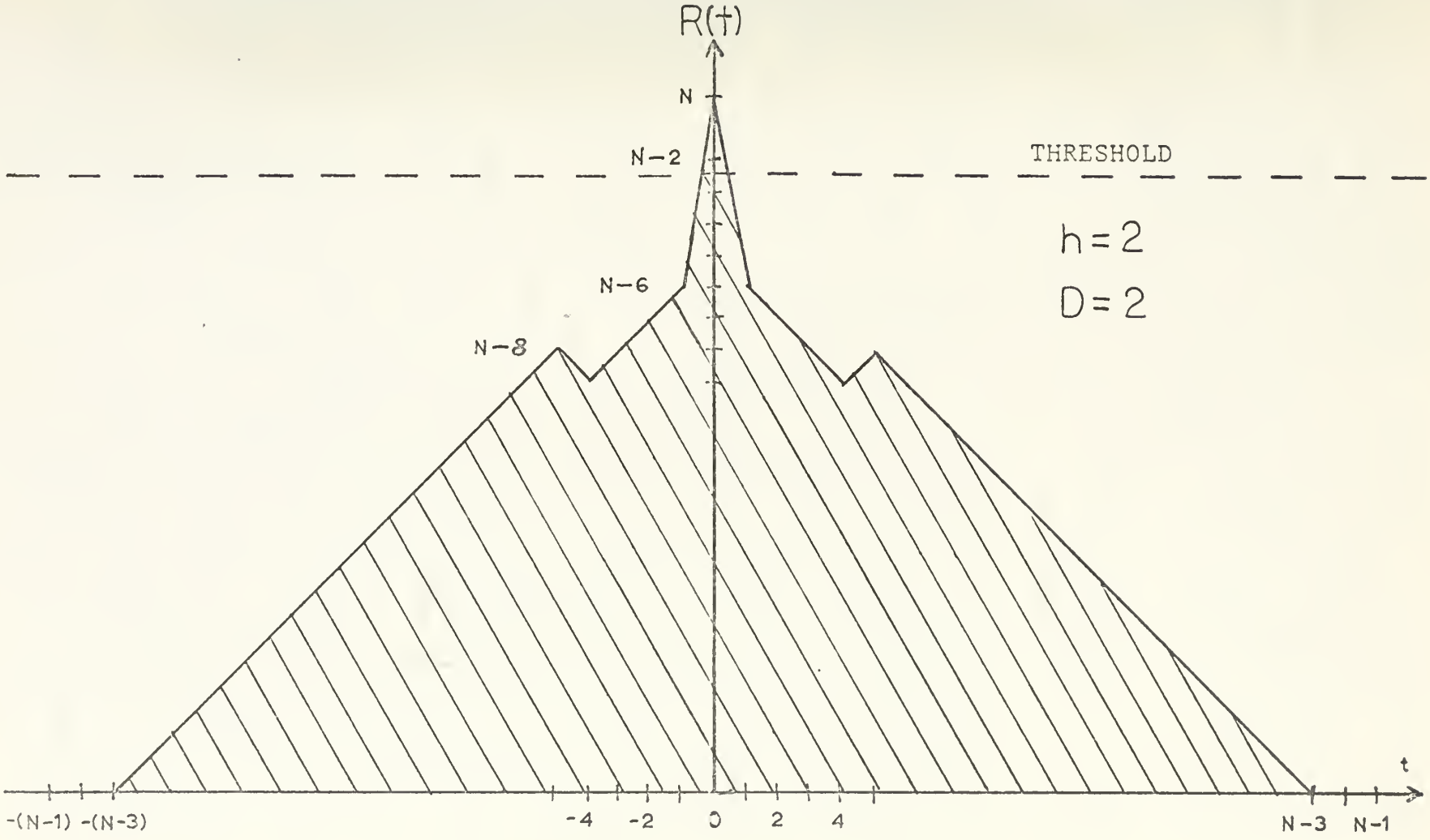

FIGURE 3-1
AUTOCORRELATION CRITERIA

In the following section, a condition for the cross-correlation function will be established. This same condition must be met by the autocorrelation function outside the aperture in order to meet specified limits on the probability of false detection during acquisition. It is listed here, in advance, in order to complete the autocorrelation specifications.

$$R(t) < N - h - t \; ; \quad 2D<t<N-h \qquad (3.1a)$$

$$R(t) = 0 \; ; \quad N-h \leq t \leq N-1 \qquad (3.1b)$$

There are 2^N sequences of length N from which to choose unique words. However, symmetry considerations can be invoked to reduce the number which must actually be checked. First, because the mod-2 summing operation is commutative, a sequence and its complement, obtained by inverting the value of each bit, have the same autocorrelation function. Second, because autocorrelation is an even function, a sequence and its transpose (or mirror), obtained by inverting the order of the bits in the sequence, have the same autocorrelation function. Therefore, once a sequence is checked it is unnecessary to check its complement, transpose or complement of its transpose. The number of required checks is not reduced by a factor of four, as it would appear at first glance, however, because the transpose and complement transpose pair may be identical to the original sequence and its complement. The required number of checks can be determined by consideration of the effect of the complement and transpose operations. Although the results were not used directly in the computer search routine, they do provide an indication of search efficiency, and are presented here as a matter of peripheral interest.

In order for the transpose or complement transpose to be identical to the original sequence, the second [N/2] bits of the sequence must be the transpose or complement transpose of the first [N/2] bits, where [N/2] equals the largest

integer less than or equal to N/2. (If N is odd, the middle bit of the sequence does not change position under the transpose operation.) The first [N/2] bits may be arranged in $2^{[N/2]}$ different ways, each arrangement having an associated transpose and complement transpose in the second half. Therefore, $2x2^{[N/2]}$ of the original 2^N sequences have redundant (identical to original sequence) transposes or complement transposes, and, for this subset, the required number of checks can be reduced by a factor of two only (by pairing a sequence with its complement). There are $2^N - 2^{[N/2]+1}$ sequences remaining to be considered. These can be grouped by fours (sequence, complement, transpose, complement transpose) to reduce the number of required checks by four. The total number of sequences of length N which must be checked in search of unique words meeting the autocorrelation condition is therefore,

$$\text{Required Checks} = \frac{2^N - 2^{[N/2]+1}}{4} + 2^{[N/2]}$$

$$= 2^{N-2} + 2^{[N/2]-1}$$

The computer program used to accomplish the autocorrelation sort is listed in Appendix D.

C. CROSS-CORRELATION CRITERIA

The cross-correlation between the unique words used by stations sharing the TDMA frame is a crucial factor affecting the false detection probability during (ungated) acquisition. A cross-correlation characteristic that yields a high probability of false detection is particularly unsatisfactory because of the periodicity of its occurrence.

In such cases, the detection aperture may be falsely set time and time again over several consecutive frames.

The probability expressions derived in Appendix C were used as a basis for the establishment of the following cross-correlation condition: the probability of false detection must be zero unless the received unique word contains one or more errors. This condition also applies to the head and tail of the autocorrelation function, outside the aperture. The cross-correlation condition is thus similar to the autocorrelation condition, differing only in that the unique word must be error free, vice h or fewer errors, to guarantee zero false detection probability. Using R(t) again to represent the correlation function, the condition on R(t) is (analogous to inequality (3.1)) $R(t)<N-h-|t|$. As the correlation function is always non-negative, this condition can be met only when $|t|<N-h$. For higher values of |t| the condition must be relaxed to $R(t)=0$. Summarizing, sets of possible unique words, having passed the autocorrelation test, are retained only if the cross-correlation between all words of the set satisfy,

$$R(t) < N - h - |t| \; ; \quad |t|<N-h \qquad (3.2a)$$

$$R(t) = 0 \; ; \quad N-h\leq|t|\leq N-1 \qquad (3.2b)$$

The conditions placed on R(t) can be used to further refine the probability expressions of Appendix C. It will be assumed that bits of fixed value (at least N-1 of them) precede the unique word and that bits of random value follow. This assumption is based on the system specifications outlined in Section I, and, although not an absolute necessity at this point, is made in order to reduce the number of situations which must be considered. Other situations, when and if occurring, may be handled in a completely analogous fashion.

First, the probability of false detection in the fixed bit region preceding a unique word (a unique word other than the one for which the detector is set) will be considered.

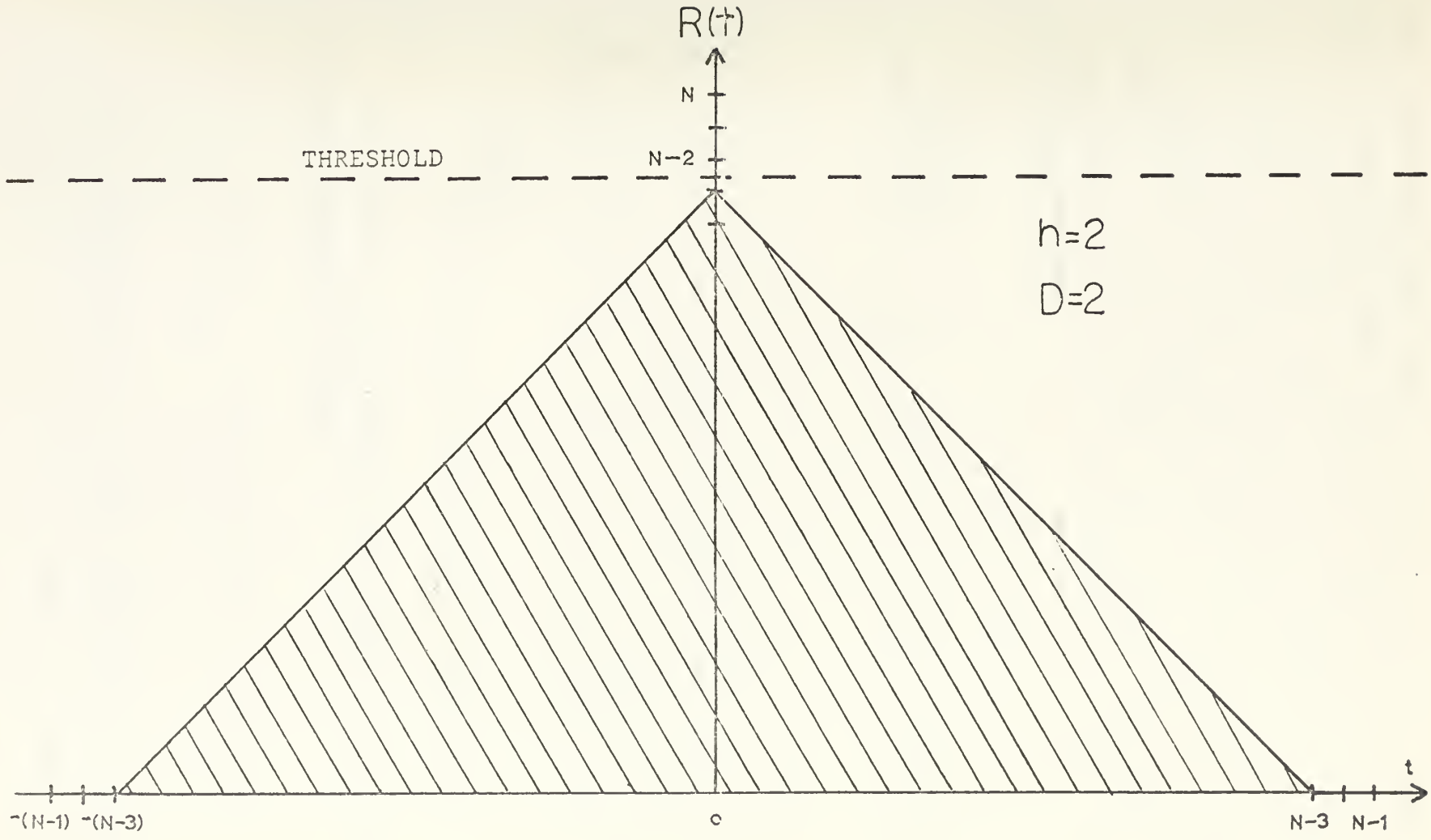

FIGURE 3-2
CROSS-CORRELATION CRITERIA

The point where the unique word is completely contained in the detector defines t=0. At t=-(N-1) the first bit of the unique word enters the detector. Equation(s) C.8 apply for $-(N-1) \leq t \leq 0$, with m=N. As in Appendix C "number of agreements" refers to matches between the detector setting and the value of the fixed bits as transmitted. The number of agreements, k in equation C.8, is equal to R(t), the number of matches within the unique word bits, plus the number of matches within the remaining |t| bits. If all of the latter match,

$$k = R(t) + |t|$$

Therefore, the cross-correlation condition 3.2a ($R(t) < N-h-|t|$) is equivalent to the equation C.8 condition,

$$k + h < N$$

The cross-correlation condition 3.2b in itself does not guarantee that $k+h<N$. It is necessary to impose the additional systems dependent condition that fewer than N-h agreements can be permitted between the non-unique word bits for $-(N-1) \leq t < -(N-h)$. Doing so, the probability of false detection at any given step is (from equation C.8e),

$$P\{A(t)\} = C(N-k, N-h-k)\, p^{N-h-k} (1-p)^{h+k}; \quad -(N-1) \leq t \leq 0 \qquad (3.3)$$

If k takes on its maximum value (N-h), the probability of false detection becomes,

$$P\{A(t)\}_{max} = (h+1)\, p\, (1-p)^{N-1}; \quad -(N-1) \leq t \leq 0 \qquad (3.4)$$

The probability of false detection in the random bit region following the unique word is also given by equation(s) C.8. In this case m equals the number of unique

word bits in the detector (there are no other fixed bits) and the number of fixed matches, k, equals R(t).

$$m = N - |t|$$

$$k = R(t)$$

Therefore, the cross-correlation condition 3.2a ($R(t) < N-h-|t|$) is equivalent to the equation C.8 condition,

$$k + h < m$$

And the probability of false detection at any given step is given by equation C.8c (with m and k given by above).

$$P\{A(t)\} = (1/2)^{N-m} C(m-k, m-k-h)\, p^{m-k-h} (1-p)^{k+h}; \quad 0<t<N-h \qquad (3.5)$$

When k takes on its maximum value ($R(t) = N-h-t-1$), equation 3.5 becomes,

$$P\{A(t)\}_{max} = (1/2)^{t} (h+1)\, p\, (1-p)^{N-t-1}; \quad 0<t<N-h \qquad (3.6)$$

For $N-h \leq t \leq N-1$, $m = h, h-1, h-2, \cdots, 1$ and $k = R(t) = 0$, giving

$$m = N - t$$

and,

$$k + h \geq m$$

The probability of false detection is (from equation C.8b),

$$P\{A(t)\} = (1/2)^{N-m} (1-p)^{m} \sum_{j=0}^{h-m} C(N-m, j) \qquad (3.7)$$

$$= (1/2)^{t} (1-p)^{N-t} \sum_{j=0}^{h-N+t} C(t, j); \quad N-h<t\leq N-1$$

Equation 3.7, unlike equations 3.3 and 3.5, is independent of parameter variation [i.e. independent of k, R(t)] and thus "maximum P{A(t)}" has no meaning.

Equations 3.3, 3.5 and 3.7 may be used to calculate the probability of false detection as each unique word in the frame is passing through the detector. Equations 3.4, 3.6 and 3.7 provide a worst case limit for these probabilities (when unique words are chosen using the cross-correlation criteria 3.2a and 3.2b). These individual fixed-bit event probabilities are the ones needed, among others, in equation C.10 to obtain an upper bound for the probability of one or more false detections (F) over the period of one frame. Or, over a narrower time span, they can be used to compute an upper bound on the probability of one or more false detections during the 2N-1 detection events surrounding a given unique word; that is, to compute,

$$F' \leq \sum_{t=-N+1}^{N-1} P\{A(t)\}$$

F' provides a means of obtaining a relative measure of the goodness of different unique word choices without having to resort to the more lengthy calculations required by equation C.10. Substituting from equations 3.4, 3.6 and 3.7,

$$F' \leq N\left[(h+1)\,p(1-p)^{N-1}\right] + \sum_{t=1}^{N-h} (1/2)^{t} (h+1)\,p(1-p)^{N-t-1}$$

$$+ \sum_{t=N-h-1}^{N-1} (1/2)^{t} (1-p)^{N-t} \sum_{j=0}^{h+t-N} c(t,j) \qquad (3.8)$$

The computer program used to check cross-correlation is listed in Appendix D. Each sequence which passes the autocorrelation test is cross-correlated with every other such sequence, yielding pairs of acceptable unique words. In order to form maximal length sets of acceptable unique words, it is necessary to perform an additional matching

routine. For example, if UW1 cross-correlates well (matches) with UW2, UW3 and UW4, then a set of three is obtained if UW2 also matches with UW3 or UW4, or UW3 matches with UW4; a set of four is obtained if UW2 matches with both UW3 and UW4 and UW3 matches with UW4. Various matching algorithms were programmed, none of which performed in a completely acceptable fashion. At N=17, the number of checks which must be performed becomes so great that, for the algorithms used, computation time runs into days. In order to obtain results for N=17 and higher, various expedients were employed, as described in the following section, to reduce the required computer time.

IV. PRESENTATION OF RESULTS

The SDS-9300 digital computer was used to perform a correlation sorting routine patterned after the criteria established in the preceding section. At the outset, it was realized that a significant amount of machine time would be required to obtain results; but, even so, the magnitude of the problem was not fully appreciated until program execution was initiated. The SDS-9300 was chosen over the IBM-360 because of the local availability of multi-hour blocks of computer time, realizing that its limited on-line memory (32K) might prove restrictive.

The choice of detector parameters and the essential findings of the computer search effort are covered in the following paragraphs. Selected sets of unique words are listed in Appendix A.

A. CHOICE OF DETECTOR APERTURE AND THRESHOLD

The motivation for use of a steady-state aperture technique is provided in Section II.B. As the aperture width must be at least 2D+1, where D is the maximum displacement of a unique word in one frame period, Table 2-1 leads one to a choice of a four or five bit width. An odd width is preferred in order that the aperture counter can be run directly off the receiver clock; i.e., so that detector activation/deactivation occurs at the beginning rather than in the middle of a bit cycle. An aperture width of five bits is thus the mimimum acceptable, and yet at the same time provides sufficient margin to cover unique word drift over more than one frame in the event of a miss-detection.

The choice of a detector threshold (h) is determined by the setting of an acceptable limit for the miss-detection probability (Q), which in turn is a function of the bit error rate (p). For this purpose, p was assigned a value of

10^{-4} [11] as being the worst-case bit error rate that could be tolerated on a satellite communication channel. Equations C.1, C.2 and C.3 were used to compute Q and the mean time between miss-detections ($\bar{M}$) for various values of N and h. The results are listed in Table 4-1. The times given for $\bar{M}$ assume a frame period of 125 usec.

Acceptable values for $\bar{M}$ occur for h=2 and higher. The fact that the probability of false detection increases with h dictates the selection of the minimum acceptable threshold; viz. h=2.

N	h	Q	$\bar{M}$
15	0	1.50×10^{-3}	83 msec
	1	1.05×10^{-6}	2 min
	2	4.55×10^{-10}	76 hrs
	3	1.36×10^{-13}	29 yrs
17	0	1.70×10^{-3}	74 msec
	1	1.36×10^{-6}	92 sec
	2	6.79×10^{-10}	51 hrs
	3	2.38×10^{-13}	17 yrs
20	0	2.00×10^{-3}	62 msec
	1	1.90×10^{-6}	66 sec
	2	1.14×10^{-9}	30 hrs
	3	4.84×10^{-13}	8 yrs

Table 4-1
Miss-Detection Probabilities

B. UNIQUE WORD SYMMETRIES

Certain characteristics of the sequences which pass the autocorrelation test were used to simplify the cross-correlation sort. These same characteristics also provide a degree of flexibility in applying the results to particular operating systems.

A sequence can pass the autocorrelation test only if its autocorrelation is zero for the first and last three values at the head and tail of the distribution (with h=2). Therefore, the first three bits of the sequence must be all zeros or all ones, and the last three bits must all be of opposite polarity. The need to check less than one-half of the total possible sequences was explained in Section III.B. As the autocorrelation sort looks at sequences in ascending order of numerical value, sequences passing the test necessarily begin with three zeros. (The search is exhausted prior to reaching sequences which have a one as the first bit on the left.) When a potential unique word (UW) sequence passes the autocorrelation test it is known that its complement (CUW), transpose (TUW) and complement transpose (CTUW) will also pass the test. The latter were computed and stored along with the UW. For example, the following sequences of length 14 pass the autocorrelation test:

UW	CUW	TUW	CTUW
00000101100111	11111010011000	11100110100000	00011001011111
00001011001111	11110100110000	11110011010000	00001100101111

The cross-correlation condition is identical to that of autocorrelation on the head and tail of the distribution. That is, the cross-correlation between sequences must be equal to zero for the first and last three values. It is obvious from the example above that cross-correlations between the UW/CTUW sequences and the CUW/TUW sequences do not meet this condition. This is true in general. Further,

because of the symmetry inherent in the complementing operation, (1) if UW1 cross-correlates well (matches) with CTUW2, then CUW1 matches with TUW2 and (2) if UW1 matches with UW2, then CTUW1 matches with CTUW2, etc. Therefore, in checking cross-correlation it is only necessary to check each UW against other UW's and CTUW's. Each set of unique words obtained by this process can be converted, by inspection, to a second set by taking the complement of each unique word. This provides a dual flexibility in applying a set to a particular operating system with its own peculiar arrangement of fixed value bits preceding the unique word.

C. UNIQUE WORD SETS

As explained above, the sequences from the classes designated CUW and TUW need not be, and were not, considered in the cross-correlation search for sets of unique words. Each set extracted from the UW/CTUW sequences has a companion within the CUW/TUW sequences, obtainable by inspection. In order to accurately reflect the computational requirements, the reported results which follow thus are drawn only from the former. That is, such quantities as "number of sequences passing the autocorrelation test" and "number of sets of length X" refer to actual computer results. The numbers can be doubled by including the complemented sequences. Computer program descriptions are included in appendix D.

Two results of primary interest were obtained for each value of N. First, the unique word which cross-correlated well with the maximum number of sequences was recorded, along with the corresponding matching sequences. These are referred to as "gated sets." These sequences may be used as unique words in a gated acquisition system where it is necessary that only the reference unique word cross-correlate well with the other unique words. That is, as all detectors except the one set for the reference are gated, only the latter must contend with non-associated

unique words during acquisition, and is thus the only one for which cross-correlation properties are of concern. Second, sets of unique words were obtained which have the property that every word in the set cross-correlates well with every other word in the set. Sets of this type are necessary for ungated acquisition, and are referred to hereinafter simply as "sets."

With h=2 and a five bit aperture width, no sequences passed the autocorrelation test for N=13 and below. At N=14, four sequences passed the autocorrelation test, but none of them could be paired in cross-correlation. At N=15, 36 sequences passed the autocorrelation test. A gated set of length 13 and a total of 16 sets of length three were obtained. The total computer search time was 25 secs.

At N=16, 150 sequences passed the autocorrelation test, and the largest gated set was of length 66. A total of 56 sets of length six were found. The computer search time was 3 min, 50 secs.

The difference in computational requirements between N=15 and N=16 was the first indication of the magnitude of the time problem which would be encountered in dealing with higher values of N. At N=17, the number of cross-correlation pairs increased to the point where it was also necessary to revise the final matching algorithm to prevent memory overflow, compounding the time problem. With 444 sequences passing the autocorrelation test, a gated set of length 272 was obtained. Several sets of length nine were found using 4+ hours of computer time, at which point program execution was terminated. It is estimated that approximately 65 hours would be required for a complete search with the algorithm being used.

It was obvious that it would be futile to continue the search to higher values of N using the same procedure. Attempts at developing a more efficient algorithm were unsuccessful. The 32K on-line memory of the SDS-9300 was a serious constraint, but even without it, the anticipated

execution time for the algorithms envisioned far exceeded the computer time that could be made available. A simple subterfuge was eventually employed to obtain partial results for higher values of N.

The number of sets of a given maximal length which were being found for higher values of N were far greater than needed in order to offer an acceptable degree of flexibility in selecting a particular set for use in an operational system. Many of the sets differed only in the replacement of one or two unique words, and, because of the nature of the searching process, tended to be uncovered within the same time frame. When the program was terminated prior to completion of a search, as at N=17, not only was it unknown whether or not sets of greater length than found actually existed, the ones that were found were for the most part different combinations of the same slightly larger set of unique words. Given the fact that a partial search must suffice, it seemed appropriate to effect a reduction in the number of sequences which passed the autocorrelation test to the point that the cross-correlation search could be run to completion. Doing so again creates uncertainty as to whether or not sets of maximal length have been found. However, given the excessive number of sets being obtained, there is some hope that some of them might still appear when the autocorrelation basis is reduced.

Increasing the effective detector aperture creates a more strict autocorrelation condition and thus reduces the number of sequences passing the autocorrelation test. A mathematically artificial increase affects detector performance only in that the probability of false detection is reduced (unnecessarily) in the region immediately outside the real aperture. The effect of a varying aperture was first tested using N=15 and N=16, for which complete results had been previously obtained. For N=15, the maximal length set remained at three for aperture widths of three through six bits. The number of such sets totaled 121 for a three

bit aperture versus six for a six bit aperture. For N=16, the maximal length remained at six for aperture widths of three through six bits, with corresponding totals of 724, 345, 56 and 8. Four sets of length five were obtained for an aperture width of seven bits.

Indeed, up to a point, the maximal length is independent of aperture variation. Partial results were obtained for values of N equalling 17, 18, 19 and 20 using this technique. The aperture was set high and then reduced in increments until search time became excessive. The results so obtained again fell short of expectations in that much computer time was still required to complete the partial search. For a given number of sequences passing the autocorrelation test, it was expected that search time would be of the same order of magnitude for the different values of N. In fact, search time increased rapidly with N. For example, with a five bit aperture, 150 sequences passed the autocorrelation test at N=16 and the total search time was 3 min, 50 sec. With a 16 bit aperture, 142 sequences passed the autocorrelation test at N=20 and the search was only approximately 1/30th complete when terminated after two hours. The imposition of a stricter autocorrelation criteria produces a basis of the same order as for a lower value of N, but the cross-correlation properties of these sequences is such that many more combinations of match sets exist. That is, any given unique word cross-correlates well with many more sequences in the N=20 basis than in the N=15 basis.

Data on the numbers of sets found with h=2 for various values of N and various aperture widths is presented in Table 4-2; "W" is the aperture width and "NAUTO" is the number of sequences passing the autocorrelation test. An asterisk denotes partial results obtained from an incomplete search. Table 4-3 contains similar data for h=1 and h=3, and serves to illustrate the effect of a varying threshold

on the numbers involved. A representative listing of maximal length sets (for h=2) is contained in Appendix A.

N	W	NAUTO	Gated Set Maximal Length	Set Maximal Length	Number of Maximal Length Sets
14	4	4	0	0	-
15	7	110	2	2	2
	6	26	7	3	6
	5	36	13	3	16
	4	60	21	3	72
	3	78	22	3	121
16	7	70	20	5	4
	6	110	47	6	8
	5	150	66	6	56
	4	190	84	6	345
	3	222	95	6	724
17	9	56	21	6	2
	7	260	145	9*	unkn
	5	444	272	9*	unkn
18	13	20	14	4	18
	12	46	26	6	63
	11	60	47	9	4
	10	142	102	10*	unkn
	9	358	254	unkn	unkn
19	15	36	26	5	89
	14	106	83	9*	unkn
	13	204	157	unkn	unkn
20	16	142	113	10*	unkn
	15	358	306	unkn	unkn

Table 4-2
Sets Obtained For h=2

h	N	W	NAUTO	Gated Set Maximal Length	Set Maximal Length	Number of Maximal Length Sets
1	10	7	4	2	2	5
		5	8	3	2	2
	11	9	8	2	0	-
		7	14	6	3	10
		5	30	13	4	20
	12	9	30	14	5	16
		7	44	25	6	20
		5	78	44	9	10
	13	9	92	54	10*	unkn
		7	130	84	11*	unkn
		5	182	120	unkn	unkn
3	19	5	0	0	0	-
	20	7	14	0	0	-
		5	76	17	4	20

Table 4-3
Sets Obtained For h=1 and h=3

D. FALSE DETECTION PROBABILITIES

The probability of miss-detection is, for constant h, the same for all sequences of a given length. Representative numbers are contained in Table 4-1. Given an acceptable combination of length and detector threshold, it is the relative values of false detection probability that then determine whether or not a particular sequence, or set of sequences, is suitable for use as a unique word. The auto- and cross-correlation criteria were established with this in mind. As a point of final analysis, the equations of Appendix C were used to calculate the false detection probabilities. Representative results are included in the following paragraphs.

1. Probability of False Detection in the Random Region

In an efficient TDMA system, the number of random (information) bits in a frame far exceeds the number of fixed bits. The majority of terms in the expression for the probability of one or more false detections per frame,

equation C.10, are therefore of the form given by equation C.4, the probability of false detection when only random bits are in the detector. With h=2,

$$P\{A(t)\}_r = 3.693 \times 10^{-3} \quad \text{for } N=15$$

$$= 2.012 \times 10^{-4} \quad \text{for } N=20$$

2. Cross-Correlation Bound

When one or more unique word bits, other than the one for which the detector is set, are contained in the detector, the cross-correlation criteria establish an upper bound on the probability of false detection (equations 3.4, 3.6 and 3.7). These individual event probabilities can in turn be inserted into equation 3.8 to obtain an upper bound for the probability of one or more false detections (F') as any one unique word passes through the detector. Several such calculations were performed; for N=15 and N=20, the results were,

$$F'_{max} = 5.831 \times 10^{-3} \quad \text{for } N=15$$

$$= 6.332 \times 10^{-3} \quad \text{for } N=20$$

Thus F' is within an order of magnitude of the individual event probabilities in the random region. Because of the typically large number of random events, F' in fact makes an insignificant contribution to the total F over the period of one frame. Given the fact that a cross-correlation false detection pulse is potentially periodic, an "insignificant" F' is precisely what is desired.

3. Example System Calculations

In order to compute the probability of one or more false detections over a frame, it is necessary to have available the specific frame composition of the operating

system in question. A system was hypothesized for the purpose of obtaining a general feeling for the relative magnitude of the different factors involved. The number of stations was set at three in order to simplify the calculations and permit selection of a set of unique words from those available at N=15. The following set was selected at random:

(1) 000001100101111
(2) 000100100011111
(3) 000101001101111

This set possesses the following correlation properties:

AUTOCORRELATION

	R(t)		
±t	(1)	(2)	(3)
0	15	15	15
1	9	9	7
2	7	7	7
3	7	7	7
4	5	6	6
5	4	4	5
6	5	3	6
7	5	5	2
8	4	4	3
9	2	2	3
10	1	1	2
11	0	1	1
12	0	0	0
13	0	0	0
14	0	0	0

CROSS-CORRELATION

	R(t)		
t	(2)-(1)	(3)-(1)	(3)-(2)
-14	0	0	0
-13	0	0	0
-12	0	0	0
-11	0	0	1
-10	0	1	2
-9	2	2	2
-8	4	3	3
-7	5	4	2
-6	5	5	5
-5	7	4	5
-4	6	5	3
-3	5	8	6
-2	7	8	10
-1	11	6	8
0	11	12	10
+1	9	10	10
+2	9	8	8
+3	9	8	8
+4	3	6	5
+5	3	3	6
+6	5	6	4
+7	3	3	5
+8	4	4	4
+9	2	3	3
+10	2	2	1
+11	1	1	1
+12	0	0	0
+13	0	0	0
+14	0	0	0

The hypothetical system is patterned after the operational system described in Ref. 3. The transmission rate is 60 Mbps (4-phase), the frame length is 750 usec, the

guard band is 24 bits in width and there are 60 fixed bits in the preamble for carrier and bit timing recovery. The latter are arbitrarily assumed to consist of a sequence of 30 1's for carrier recovery, followed by a sequence of 30 alternating 0's and 1's for bit timing recovery. Bits are clocked in from the left, with the detectors set to the unique words as listed above.

It is first necessary to determine the number of random versus fixed detection events per frame. The product of the transmission bit rate and frame length gives the number of bits in one frame, n=45000. The beginning of each station's burst is composed of 75 fixed value bits (recovery plus unique word). When one or more of these bits is in the detector, the detection event is, by definition, "fixed." Therefore, for each station's burst, there are 75 fixed detection events as each bit, from the first to the last, is clocked into the detector; plus an additional 15 fixed events as the last bit, and those immediately preceding it, are clocked out of the detector. The total number of fixed detection events per frame is thus equal to 270 (3x90). The number of random events is 44730 (45000-270).

With this number of random events, the upper bound on the probability of one or more false detections per frame in the random region alone is (equation 3.10),

$$F \leq rP\{A(t)\}_r = 44730(3.693 \times 10^{-3})$$

$$F \leq 165$$

which is not a particularly enlightening result for a probability upper bound. It is indicative, however, of the fact that a false detection is almost certain during acquisition. By way of comparison, the Ref. 11 expression

for the probability of no false detection in the random region gives,

$$1 - F = [1 - P\{A(t)\}_r]^{44730} = 1.3 \times 10^{-72}$$

Therefore, it can be concluded that many false detections will occur during the acquisition phase, and that, for the system design hypothesized, little can be done to improve the situation, short of using some type of acquisition gate. This is generally true for the typical prototype TDMA systems which have been developed. No attempt was made to compute the expected acquisition time, a subject treated extensively in Ref. 11.

If an acquisition gate is employed, the detector is active for a maximum of 2B=48 detection cycles prior to the receipt of the associated unique word. All of these are fixed detection events. At each cycle, the autocorrelation values can be added to the number of matches occurring in the recovery bits to obtain the number of total fixed matches, k. Equation C.8e can then be used to obtain an upper bound on F. Doing so, for detector number (2),

$$F \leq 3.996 \times 10^{-11}$$

$$\bar{F} \geq 2.503 \times 10^{10} \text{ frames} = 217 \text{ days}$$

For detector number (3),

$$F \leq 5.993 \times 10^{-4}$$

$$\bar{F} \geq 1669 \text{ frames} = 1.25 \text{ sec}$$

The mean time between false detections ($\bar{F}$) is more than acceptable for both, indicating a high probability of achieving acquisition in just one pass of the unique word. Acquisition of the reference unique word, assumed to be

number (1) here, must still be effected without benefit of gating, and thus remains a potentially time consuming process.

V. CONCLUSIONS

This research effort was undertaken for the express purpose of finding unique word sequences which would be suitable for use in a TDMA satellite communication system. The correlation properties of potential unique words were of primary concern in this effort, criteria being established which would insure a low probability of false detection. Numerous sets of unique words were found using these criteria.

The results obtained can not, unfortunately, be applied to any given operational TDMA system without some additional consideration of false detection probabilities. In an attempt to generalize findings, it was necessary to ignore the fact that each system has its own peculiar set of fixed value bits, in addition to the unique words, which are transmitted in each station's burst. These fixed value bits are in fact an extension of the unique word sequence and produce a cross-correlation distribution of their own when passing through a detector. The cross-correlation may very well be such that a set of unique words selected at random from this work would prove unacceptable. Fortunately, the number of sets available of any given length, together with the existence of the complementary options, provides a flexibility sufficient to cover any foreseeable situation.

The length of the sets found fell short of expectations. To begin with, in setting cross-correlation criteria based on worst-case possibilities for the number of detector agreements, unique words which might actually be useable in a particular system were excluded. That is, the number of agreements produced when non-unique word fixed bits are stepping through the detector can seldom be expected to approach the worst-case limit. This fact was noted at the outset, however, and accepted in order to generalize the

results as much as possible. The real disappointing factor was that, even with the strict correlation criteria, a computer search could not be designed to uncover with certainty the sets of maximal length for values of N in excess of sixteen.

There is a need for an efficient algorithm for combining unique words into sets possessing good cross-correlation properties. As stated in Ref. 11, the problem is a puzzling one. It is a problem which can undoubtedly be solved only by adopting some type of short-cut technique, wherein but a few of all the multitude of different matching combinations are considered. The ability to predict the maximal length for a given N would be of tremendous benefit in this regard.

The ultimate achievement would be the discovery of an underlying structure which enabled one to extract unique word sequences without the need to resort to brute force computer search techniques.

APPENDIX A
UNIQUE WORD SETS

Selected sets of unique words, representative of the many found, are presented herein. The listing for N=15 is complete. In the interest of space, unique words are listed in octal format. All sets are valid for a detector threshold setting of two.

A "gated set" is one in which the first sequence listed (the supposed reference) cross-correlates well with all the sequences which follow. A "complete set" is one in which each sequence cross-correlates well with every other sequence.

N=15

MAXIMAL LENGTH GATED SET

01457	01347	02067	02327	02367	02467	03067
	04437	05157	04157	04657	04517	04117

COMPLETE SETS

(1)	00627	02067	02217	(9)	01667	02367	02717
(2)	06627	02217	02327	(10)	01667	02367	02637
(3)	06627	02217	02367	(11)	01667	03367	02637
(4)	01317	01667	02327	(12)	05477	04757	03557
(5)	01457	04437	05157	(13)	05477	03557	05157
(6)	01457	04437	04157	(14)	05477	03557	04157
(7)	01457	04437	04117	(15)	03137	04437	05157
(8)	01667	02327	02637	(16)	04437	04157	03057

N=16

MAXIMAL LENGTH GATED SET

002637	001627	001647	001667	002247	002327	002347
	002367	002467	002647	003067	003127	003267
	003327	003347	003367	003557	003667	004157
	004167	004327	004367	004517	004617	004627
	004657	004717	004727	005167	006167	006267
	006467	006567	006767	014277	011737	012337
	014337	010337	011537	014537	006137	014137
	011637	011237	014237	010237	006757	004757
	010757	012357	010357	006557	005157	006157
	010157	011657	006657	010657	006257	011457
	010457	010717	011517	010517	010617	

COMPLETE SETS

(1)	001457	002717	005317	011237	010657	011517
(2)	001667	002637	004657	005167	006467	006157
(3)	002367	005167	006467	005477	006137	006257
(4)	002467	002637	003267	004367	006137	006257
(5)	002637	003267	004367	006467	006137	006257
(6)	002637	003267	005167	006467	006137	006257
(7)	002637	004657	006137	011237	010357	011457
(8)	002717	005317	010337	003137	010657	011517
(9)	003057	004567	005067	006267	004437	005157
(10)	003267	004367	004717	005467	003137	005157
(11)	003557	011537	005637	010557	011657	011317
(12)	004567	005067	006267	006137	004437	005157
(13)	004417	003137	004437	005157	010157	011517
(14)	005317	011077	010337	003137	010657	011517

N=17

COMPLETE SETS

(1)	001667	006257	011057	011167	012467
	014457	012157	011437	014237	
(2)	003137	005567	005717	007157	007327
	011767	012667	012717	013167	
(3)	003327	005567	007157	007267	011767
	012667	012717	013167	021017	
(4)	002637	021137	014137	011437	024437
	024157	022257	014257	021457	
(5)	002717	003237	005567	006327	007267
	007317	011727	012267	013167	
(6)	003137	005667	005717	006727	007157
	011767	012267	012717	013167	
(7)	005567	005717	006657	007157	007267
	011727	012667	012717	013167	
(8)	005717	006657	006727	007267	007567
	011767	012667	012717	013167	

N=18

COMPLETE SETS

(1)	001457	004767	011637	014657	015527
	020567	021667	025517	014337	024637
(2)	004657	004767	005717	012717	015727
	016667	021767	026317	006277	014337
(3)	012717	014657	025517	044177	040677
	006277	014337	045437	041357	022357
(4)	014657	030277	042477	043337	050337
	053637	045437	042757	022357	044357
(5)	021557	044177	042677	024677	030537
	050637	045437	041357	022357	031257

N=19

COMPLETE SETS

(1)	0004657	0005567	0005637	0006767	0007557
	0010767	0011167	0030577	0042277	0022477
(2)	0004657	0005637	0007557	0013357	0015757
	0104577	0106677	0014277	0101477	0022477
(3)	0007557	0011537	0013357	0013477	0015757
	0104577	0106677	0014277	0101477	0022477
(4)	0007557	0013357	0013477	0015757	0046577
	0104577	0101177	0106677	0014277	0101477

N=20

COMPLETE SETS

(1)	0004437	0006277	0023477	0030737	0064577
	0061177	0054677	0024677	0043277	0040477
(2)	0004437	0007137	0011537	0013237	0015637
	0021137	0024337	0030737	0030277	0045477
(3)	0007137	0011077	0013237	0015637	0021337
	0032737	0060577	0054677	0047277	0041477
(4)	0013237	0013477	0014277	0020677	0032737
	0035737	0062577	0050677	0042277	0047477
(5)	0021137	0023077	0024477	0024737	0030337
	0064377	0035577	0054577	0036677	0043477

APPENDIX B
DETERMINATION OF BURST DRIFT RATE

In the absence of transmitter burst position corrections and under zero doppler conditions, a given unique word will be received every T seconds. (Other factors, such as clock stability and logic jitter, affect this periodicity; however, they are inconsequential compared to potential doppler effects and will be ignored.) Burst drift is defined as the doppler induced, real-time shift of a burst from its periodic position.

Burst drift rate is a function of the relative velocity between transmitting station, satellite and receiving station. Interest here is in determination of the maximum drift rate that can be expected. First, let us consider the motion of the typical communication satellite in an equatorial, geosynchronous orbit. Ideally, such a satellite remains at the same altitude over a given point on the equator. In reality, it is physically impossible to achieve and maintain a perfectly synchronous orbit [12]. Reference 13 derives equations which can be used to estimate the worst-case relative velocity between a geosynchronous satellite and a given point on the earth's surface. The orbit eccentricity and inclination are the two primary factors which influence the satellite's motion.

A non-circular orbit results in a sinuscidal variation of the satellite altitude. To a first order approximation, the resulting doppler shift is independent of earth station coordinates. If e is the eccentricity of the orbit, the maximum relative velocity is approximately,

$$v_e = 12100e \text{ Km/hr} = 3361e \text{ m/sec}$$

Using .0004 from Table 1 of Ref. 14 as a typical eccentricity for later generation communication satellites,

$$v_e = 1.3 \text{ m/sec}$$

When the orbit is inclined from the equatorial plane, the satellite moves in a figure-8 pattern, elongated north and south. The north-south motion predominates and is sinusoidal in nature. If i is the orbit inclination in radians, the resulting maximum relative velocity as seen by a station at latitude L can be approximated by,

$$v_i = 2092i\sin(L) \text{ Km/hr} = 581i\sin(L) \text{ m/sec}$$

Satellite visibility extends to approximately 80° latitude. At this latitude, the satellite appears just above the horizon and relative velocity due to orbit inclination is a maximum. (It is in fact highly unlikely that a station would attempt to use a satellite below 10° in elevation.) Thus, assuming a maximum inclination of 3° (.052 rad) and L=80°,

$$v_i = 29.7 \text{ m/sec}$$

A pessimistic estimate of the maximum relative velocity due to satellite motion alone can be obtained by combining the effects of orbit eccentricity and inclination, giving,

$$v_s = v_e + v_i = 31 \text{ m/sec}$$

Next, the contribution of earth station motion must be considered. Reference 13 analyzes the headway, roll and pitch components of ship motion and concludes that the maximum possible relative velocity contribution is,

$$v_g = 38 \text{ m/sec}$$

For a shipboard platform, then, the maximum relative velocity between ground station and satellite is,

$$v = v_g + v_s = 69 \text{ m/sec}$$

With representative numbers for satellite and surface platform motion in hand, it is next necessary to consider how they might combine to produce a shift in the position of a received unique word. The case of a station receiving its own unique word (transmitted up to the satellite and back) is a simple two-station relative motion problem and the well-known doppler equation applies.

$$d = 2vf/c \qquad \text{(B.5)}$$

where f is the transmitted bit rate and c the speed of light.

The case of a station receiving another's unique word is a three-station motion problem. Maximum doppler occurs when the maximum relative velocity exists between both ground stations and the satellite simultaneously; that is, when maximum up-link doppler is combined with maximum down-link doppler. Such a situation is produced when both ground stations are at the same 80° latitude and both are either opening or closing the satellite at the maximum rate. For this case also, then, with maximum relative velocity, v, existing between <u>both</u> stations and the satellite, equation B.5 applies.

APPENDIX C
DETECTION PROBABILITIES

Expressions for the probability of missed and false detections are derived in the following paragraphs. These expressions depend somewhat on general detector operation, but not to the extent that their application is restricted narrowly to any one particular system.

A. MISS-DETECTION PROBABILITY

If the bit error rate (BER), i.e. the probability that a received bit will be in error, is p and the number of bits in a unique word is N, then, assuming errors occur independently, the probability of a unique word being received error-free is $(1-p)^N$. With the detector threshold set at h, a unique word will be detected if it contains h or fewer errors. The probability of detection, P, is thus obtained by summing terms in the binomial distribution which correspond to the probability of no errors, the probability of one error, up to the probability of h errors. Using C(N,i) to represent the binomial coefficient $N!/i!(N-i)!$, P is given by,

$$P = \sum_{i=0}^{h} C(N,i)\, p^{i} (1-p)^{N-i} \qquad (C.1)$$

The miss-detection probability (the probability of receiving a unique word with more than h errors) is given by,

$$Q = 1-P = \sum_{i=h+1}^{N} C(N,i)\, p^{i} (1-p)^{N-i} \qquad (C.2)$$

The mean time between miss-detections is equal to the reciprocal of the expected value of "number of misses per unit time." As there is only one possible miss-detection

event per frame, the expected value is equal to the miss-detection probability, Q, and the mean time between miss-detections is,

$$\bar{M} = Q^{-1} \text{ frames} = TQ^{-1} \text{ secs} \qquad (C.3)$$

B. PROBABILITY OF FALSE DETECTION

The following notation will be used in developing expressions for false detection probabilities:

A(t)	A false detection event at time t. Used interchangeably with "A_t."
P{A(t)}	The probability of A(t).
B(t)	No false detection at time t. Used interchangeably with "B_t."
P{B(t)}	The probability of B(t).
t	An integral time variable, the basic unit of which is one bit cycle (t=ib).

On any given bit cycle, other than the one in which the actual unique word is completely contained in the detector, a false detection pulse will be produced if N-h or more of the N bits in an active detector match with the detector setting ($R \geq h$). The probability of this occurring depends on whether or not the value of transmitted bits are fixed or variable. The beginning portion of each burst is composed of fixed-value bits (timing recovery and unique word), while the remainder of the burst contains bits of variable value. The probability of one of the latter being transmitted as a '0' or a '1' depends on the type of information transmitted. As a first order approximation, it will be assumed that the variable bits are in fact random, taking on the value '0' and '1' with equal probability. With random bits alone in

the detector, the probability of a false detection on any given bit cycle is,

$$P\{A(t)\}_r = \sum_{i=0}^{h} C(N,i)\,(1/2)^i\,(1/2)^{N-i}$$

$$= (1/2)^N \sum_{i=0}^{h} C(N,i) \qquad (C.4)$$

The probability of false detection is not so easily computed when there are fixed value bits in the detector. "Fixed value" is used to denote those bits in the preamble which are transmitted with the same value ('0' or '1') in each frame. Because of the presence of transmission errors, these bits may actually be received with the opposite value, the probability of which is p. An expression for the probability of false detection can be derived based on the number of fixed bits in the detector and the number that matched with the detector setting when transmitted. Such an expression must account for all the possible combinations of errors within the fixed bits and as such will include additive terms containing higher powers of p. With $p<<1$, a good approximation can be obtained by discarding all terms which contain other than the lowest power of p. Therefore, rather than derive a complex general expression from which an approximation can be drawn, the condition $p<<1$ will be invoked at the outset in order to simplify the derivation.

Suppose there are m fixed bits in the detector and that k of them matched with the detector setting when transmitted. A false detection will occur when the number of agreements within the fixed bits, plus the number of agreements within the remaining N-m random bits is greater than or equal to N-h. With $p<<1$, interest can be focused on those particular combinations which require the fewest number of transmission errors in order to produce a false detection. Three separate cases will be considered.

CASE 1. The number of fixed agreements, k, is greater than or equal to N-h. A false detection is assured if the m fixed bits are received error free, and the probability of false detection can be approximated by,

$$P\{A(t)\}_f = (1-p)^m; \quad k+h \geq N \qquad (C.8a)$$

CASE 2. The number of fixed agreements, k, is less than N-h, but enough random bits (N-m of them) remain to produce a total of N-h or more agreements. That is,

$$k + N - m \geq N - h$$

or,

$$k + h \geq m$$

A false detection will be produced when there are no errors in the fixed bits and N-k-h or more agreements within the random bits; or, equivalently, when there are

$$N - m - (N - k - h) = k + h - m$$

or fewer disagreements within the random bits. The probability of false detection can thus be approximated by multiplying the probability of receiving the m fixed bits error free by the probability that the N-m random bits will contain k+h-m or fewer disagreements.

$$P\{A(t)\}_f =$$

$$(1-p)^m (1/2)^{N-m} \sum_{i=0}^{k+h-m} C(N-m,i); \quad m \leq k+h < N \qquad (C.8b)$$

CASE 3. The number of fixed agreements, k, plus the number of random bits, N-m, is less than N-h; i.e., k+h<m. A false detection can not occur unless there are errors in the fixed bits. The fewest number of errors are required when all of the random bits and all of the original k bits

match with the detector setting. In this case, enough errors must occur in the remaining m-k fixed bits to produce N-h agreements (the minimum required for false detection). The number of errors required is,

$$a = N - h - (k + N - m)$$
$$= m - k - h$$

The probability of false detection can thus be approximated by taking the product of (1) the probability that the N-m random bits will all match with the detector setting, (2) the probability of receiving the original k matching bits error free and (3) the probability that the m-k fixed bits will contain 'a' errors.

$$P\{A(t)\}_f = (1/2)^{N-m} (1-p)^k C(m-k,a)\, p^a (1-p)^{m-k-a}$$

$$= (1/2)^{N-m} C(m-k,a)\, p^a (1-p)^{m-a}$$

$$= (1/2)^{N-m} C(m-k,m-k-h)\, p^{m-k-h} (1-p)^{k+h}; \quad k+h<m \qquad \text{(C.8c)}$$

If <u>all</u> the bits in the detector are fixed, the probability of false detection in any given bit cycle is given by equations C.8a and C.8c with m=N.

$$P\{A(t)\}_f = (1-p)^N; \quad k+h \geq N \qquad \text{(C.8d)}$$

$$P\{A(t)\}_f = C(N-k,N-k-h)\, p^{N-k-h} (1-p)^{k+h}; \quad k+h<N \qquad \text{(C.8e)}$$

1. <u>Joint Probabilities</u>

Equations C.4 and C.8 give the probability of false detection for a single detection event within the frame. Calculation of the probability of false detection over

several consecutive bit periods, specifically over one frame, is complicated by the fact that successive detection events are not independent; i.e.,

$$P\{A(t),A(t+1)\} \neq P\{A(t)\}P\{A(t+1)\}.$$

That this is true can be seen by noting that successive detection events are generated by shifting the contents of the shift register by one bit. If a false detection does (or does not) occur at one step, possibilities for the contents of the shift register are necessarily restricted to certain combinations of bit values. These bit values carry over to the next detection event and reduce the sample space accordingly. As a simple, extreme example, consider the case of the unique word 101010. The probability of false detection with random bits in the detector and a zero threshold setting is, from equation C.4, $(0.5)^6$. However, given that a false detection occurs (the detector contains 101010), the detector will contain X10101 on the next step and the probability of false detection is zero.

Dependent joint probabilities are best dealt with by looking for, and finding, grounds for the assumption of independence. Schrempp and Sekimoto [11] based their independence assumption on the previous work of Hill [14]. The validity of this assumption is nearly impossible to access without making lengthy comparative calculations for unique words of different length, a task of monumental proportions. Rather than attempt to justify such an assumption here, joint probabilities will be expressed in terms of an upper bound.

There are n detection events per frame during acquisition, n-1 of which may produce false detections. Defining t=0 at the point when the associated unique word is completely contained in the detector, the probability of no

false detection during a frame period is given by,

$$H = P\{B_1, B_2, \cdots, B_{n-1}\} \tag{3.9}$$

$$= P\{B_1\}P\{B_2/B_1\}P\{B_3/B_1 B_2\}\cdots P\{B_{n-1}/B_1 B_2 \cdots B_{n-2}\}$$

Or, from a different viewpoint, if F is the probability of one or more false detections per frame,

$$H = 1 - F$$

$$F = \sum_{i=1}^{n-1} P(A_i) - \sum_{i=1}^{n-1}\sum_{j=i}^{n-1} P(A_i, A_j)$$
$$+ \sum_{i=1}^{n-1}\sum_{j=i}^{n-1}\sum_{k=j}^{n-1} P(A_i, A_j, A_k) - \cdots$$
$$\pm P(A_1, A_2, \cdots, A_{n-1})$$

For straight-forward calculations, F is obviously orders of magnitude more difficult to obtain than is H. However, its form does offer possibilities for reducing the complexity of the problem. Although successive events are not independent, events separated by more than N detection cycles are -- after N detection cycles, all bits from the first event have been shifted out of the detector. For $j \geq i+N$,

$$P\{A_i, A_j\} = P\{A_i\}P\{A_j\}$$

and similarly for higher order joint probabilities. If $P\{A(i)\} << 1$, these product terms are small compared to the individual terms from the first summation in F. However, for the dependent joint probabilities it is quite possible that

$$P\{A_i, A_j\} = P\{A_i\}P\{A_j/A_i\}$$

is of the same order as $P\{A_i\}$. The same can be said for higher crder terms, but with a decreasing expectation cf its actually prcving true. It is therefore not possible to discard as insignificant all of the terms involving joint probabilities. The most that can be said is that,

$$P\{A_i\} \geq P\{A_i, A_j\} \geq P\{A_i, A_j, A_k\} \bullet \bullet \bullet$$

And that,

$$F \leq \sum_{i=1}^{n-1} P\{A_i\}$$

The false detection probabilities P{A(i)} are obtainable from equations C.4 and C.8 as appropriate. For the random detection events (equation C.4), P{A(i)}=P{A(j)}; for the fixed detection events, the probabilities must be computed individually. If there are r random false detection events and f=n-1-r fixed false detection events per frame,

$$F_{max} = \sum_{i=1}^{n-1} P\{A_i\}$$

$$= rP\{A(t)\}_r + \sum_{f} P\{A(t)\}_f \qquad (C.10)$$

When the detector is gated during acquisition, as described in Section II.C, the detector is active for only 2B+1 bit cycles about the nominal position of the associated unique wcrd. The true detection pulse may occur anywhere within the aperture, depending upon the amount of displacement of the unique word from its ncminal position, and the maximum number of false detection events is equal to 2B. The probability of one or more false detections in the aperture prior tc the receipt of the unique word is therefore of the same form as equation C.10, with the number of events equal to 2B vice n-1.

In the steady-state mode, the aperture width is 2D+1 and the maximum number of false detection events is equal to 2D.

In summary, equation C.10 provides a bound on the probability of one or more false detections over one frame period, or, with a change of limits, over an acquisition or steady-state detection aperture. This bound is useful in estimating the frequency of false detections and in assessing the relative merits of different unique word combinations.

As an aside, it is interesting to compare the random event term of equation C.10 with the results of Ref. 14, obtained by assuming independent events. For random bit detection events, it was concluded that,

$$F = 1 - [1 - P\{A(t)\}]^r$$

Expanding,

$$F = 1 - [1 - rP\{A(t)\} + C(r,2)\ P\{A(t)\}^2 - \cdots]$$

For $P\{A(t)\} \ll 1$, a basic assumption of Ref. 14, an approximate expression for F is,

$$F = rP\{A(t)\}$$

Which is identical to the random bit term in equation C.10.

2. Mean Time Between False Detections

A false detection, both in the acquisition and steady-state modes, deactivates the detector and sets an aperture for the next frame. The probability of cycling through several successive detection events without any false detections is therefore of primary concern. From the opposite viewpoint, it is the probability of one or more false detections over a given time span which is meaningful, not the probability of false detection at any given step. This distinction is important in deciding upon what to use

as an appropriate measure of "mean time between false detections" (MTBFD), and in turn interpreting its meaning.

If the detector were not deactivated by a false detection pulse, several false detections might occur over the pericd of one frame. The MTBFD would then be equal to the reciprocal of the expected value for "number of false detections per frame." With detector deactivation, only one false detection per frame can actually occur and the MTBFD is affected accordingly. In this case, for computational purposes, the probability of a real, physical false detection pulse occurring somewhere within the frame is equal to F, the probability of one or more false detections per frame. The MTBFD is therefore equal to the reciprocal of F and can be bounded by substitution from equation C.10.

$$\bar{\mathcal{F}} = F^{-1} \geq F_{max}^{-1} \text{ frames} \qquad (C.11)$$

APPENDIX D

COMPUTER PROGRAM

The computer program was written, and debugged, in three separate functional segments and then patched together to form one continuous program. These segments will be described and listed separately. The last segment listed is the basic cross-correlation matching routine. Several different revisions were employed in an attempt to overcome time and memory limitations.

Arrays

GUW(IDIM) - Sequences which pass the autocorrelation test.

GCTUW(IDIM) - Complement transpose of GUW.

GTUW(IDIM) - Transpose of GUW.

GCUW(IDIM) - Complement of GUW.

MTEMP(IDIM2) - Used for temporary storage of good cross-correlation matches.

INCR( ) - Used to store pointers needed in the cross-correlation matching process. Dimension greater than or equal to maximal length set expected.

MATCH(IDIM1,IDIM2) - Matrix in which good cross-correlation matches are recorded.

MCROSS(2IDIM) - Sequences from autocorrelation sort which are checked for cross-correlation (the GUW and GCTUW subsets).

Equivalence Statement - The first half of MCROSS is stored in same memory location as GUW( ); the second half in same location as GCTUW( ).

Variables Common to All Segments

UW - Sequence under test.

SUW - Shifted version of UW. A sequence is shifted one bit at a time and, at each step, added mod-2 to UW.

TUW - Transpose of UW.

CTUW - Complement transpose of UW.

CUW - Complement of UW.

N - Length of sequences being tested (Input).

IEPS - Threshold; h of thesis main body (Input).

IALFA - Aperture parameter; equals 2D (Input).

NUW - Number of good UW's obtained in autocorrelation sort.

NAUTO - Number of UW's and CTUW's, combined, which are checked for cross-correlation; equals 2NUW.

Autocorrelation Sort

Variables

K - Smallest integer equal to or greater than N/2.

LAST,LAST1 - Intermediate skip points in the sequential checking process. Sequences which must be checked tend to occur in blocked subsets, with two redundant sequences separating each.

IZ1 - Next to last sequence which must be checked.

IZ2 - Last sequence which must be checked to insure all possible non-redundant sequences have been considered.

MASK - Binary constant consisting of N 1's, right justified. Used to obtain the complement of an N bit sequence.

IFLAG - Set to one when last sequence being checked. Keys the termination of autocorrelation search.

JFLAG - Set to one when autocorrelation condition requires R(t)=0. Autocorrelation computation for a particular UW is complete when JFLAG=IEPS.

I - Shift variable. Equivalent to time variable of thesis main body.

ICOUNT - The autocorrelation value at step I.

Output

The sequences which pass the autocorrelation test, and the corresponding CUW's, TUW's and CTUW's, are output in side-by-side decimal and octal format.

Program

```
      INTEGER UW,SUW,TUW,CTUW,CUW,GUW(73),GCTUW(73),
     1GTUW(73),GCUW(73),MTEMP(110),INCR(30),MATCH(73,110),
     2MCROSS(146)
      EQUIVALENCE(GUW(1),MCROSS(1)),(GCTUW(1),MCROSS(74))
C INITIALIZATION AND PARAMATER INPUT
      IDIM=73
      IDIM1=73
      IDIM2=110
1     READ(5,500) N,IEPS,IALFA
      WRITE(6,505) N,IEPS,IALFA
      IF(N.EQ.(N/2)*2) GO TO 5
      K=(N+1)/2
      LAST=2**K-2
      LAST1=2**(K+1)-2
      GO TO 10
5     K=N/2
      LAST=2**(K+1)-2
      LAST1=2**(K+2)-2
10    IZ1=1
      MLAST=N-2
      DO 15 M=K,MLAST
15    IZ1=IZ1+2**M
      IZ2=2**(N-1)-2
      MASK=2**N-1
      IFLAG=0
      UW=0
      J=1
      L=1
      JFLAG=0
C INITIALIZE FOR AUTO-C OF NEXT UW
20    I=0
      SUW=UW
C COMMENCE AUTO-C LOOP.
C THE FOLLOWING IN-LINE SEGMENT INITIALIZES AN N-I COUNTER,
C LOADS SUW INTO A-REGISTER, SHIFTS SUW RIGHT ONE BIT,
C STORES RESULTS IN "SUW" FOR LATER USE, COMPUTES MOD-2 SUM
C OF UW AND SUW, COUNTS NUMBER OF ZEROS IN FIRST N-I
C POSITIONS (FROM RIGHT) OF THE MOD-2 SUM.
30    I=I+1
      ICOUNT=0
S     LDA N
S     SUB I
S     ADD =077677777
S     RCH 070100,1
S     LDA SUW
S     SHIFT C21001
S     STA SUW
S     EOR UW
S     SHIFT 01001
S     SKB =040000000
S     MPC ICOUNT
S     BRX $-3,1
C ARE WE INSIDE APERTURE?
      IF(I.LE.IALFA)GO TO 31
C ARE WE ON DISTRIBUTION TAIL?
      IF(I.GE.N-IEPS) GO TO 32
C DOES UW PASS AUTO-C TEST AT STEP I OUTSIDE APERTURE?
      IF(ICOUNT.LT.N-IEPS-I) GO TO 30
      GO TO 35
C DOES UW PASS AUTO-C TEST AT STEP I INSIDE APERTURE?
31    IF(ICOUNT.LT.N-2*IEPS-I) GO TO 30
      GO TO 35
C DOES UW FAIL ZERO TEST ON DISTRIBUTION TAIL?
32    IF(ICOUNT.NE.0) GO TO 35
C NOW ON DISTRIBUTION TAIL
```

```
33      JFLAG=JFLAG+1
        IF(JFLAG.LT.IEPS) GO TO 30
C HAVE GOOD UW.  COMPUTE CUW, TUW, CTUW.
C THE FOLLOWING IN-LINE SEGMENT INITIALIZES AN N COUNTER,
C LOADS UW INTO A-REGISTER, FORMS TRANSPOSE OF UW BY RIGHT
C SHIFTING ONE BIT AT A TIME INTO B-REGISTER AND THEN CYCLE
C (END-AROUND) SHIFTING THE LATTER, FORMS COMPLEMENT OF
C BOTH UW AND TUW USING MASK OF ONES.
SS      LDA N
SS      ADD =077677777
SS      RCH 070100,1
SS      LDA UW
SS      RCH 037710
SS      SHIFT C1001
SS      SHIFT C16002
SS      BRX $-2,1
SS      SHIFT C11001
SS      STE TUW
SS      LDA UW
SS      EOR MASK
SS      STA CUW
SS      LDA TUW
SS      EOR MASK
SS      STA CTUW
C HAVE WE PREVIOUSLY CHECKED AND STORED THESE SEQUENCES?
        IF(TUW.LT.UW.OR.CTUW.LT.UW) GO TO 35
C DIMENSION OVERFLOW CHECK
        IF(L.GT.IDIM) GO TO 47
C STORE GOOD SEQUENCES
        GUW(L)=UW
        GCUW(L)=CUW
        GTUW(L)=TUW
        GCTUW(L)=CTUW
        L=L+1
C PICK A NEW SEQUENCE
35      IF(UW.LT.LAST) GO TO 40
        IF(UW.GE.IZ1) GO TO 45
        IF(UW.LT.LAST1) GO TO 52
        J=J+1
        IF(N.EQ.(N/2)*2) GO TO 50
        LAST1=2**(K+J)-2
        GO TO 52
50      LAST1=2**(K+J+1)-2
52      LAST=LAST+2**(K-J)
        UW=UW+3
55      GO TO 20
40      UW=UW+1
        GO TO 20
45      IF(IFLAG.EQ.1) GO TO 60
        IFLAG=IFLAG+1
        UW=IZ2
        GO TO 20
C DIMENSION OVERFLOW HALT
47      WRITE(6,506) UW
        STOP
C COMPUTE NUW AND NAUTO
60      L1=L-1
        NUW=L1
        NAUTO=2*NUW
C OUTPUT GOOD SEQUENCES (DECIMAL AND OCTAL FORMAT)
        WRITE(6,507)
        DO 65 M=1,L1
65      WRITE(6,508) M,GUW(M),GUW(M),GCUW(M),GCUW(M),GTUW(M),
       1GTUW(M),GCTUW(M),GCTUW(M)
C
500     FORMAT(3I10)
505     FORMAT('1','N=',I2,10X,'IEPS=',I1,10X,'IALFA=',I2)
506     FORMAT('0','AUTOCORRELATION SEARCH TERMINATED TO',
       1' PREVENT DIMENSION OVERFLOW. LAST WORD CHECKED:',I6)
507     FORMAT('0','UNIQUE WORDS WHICH PASS AUTOCORRELATION',
       1' TEST'//18X,'UW',25X,' CUW',25X,'TUW',25X,'CTUW'//)
508     FORMAT(' ',I3,5X,4(I6,3X,O10,8X))
```

Cross-Correlation Sort

Variables

M2 - Number of sequences with which sequence being tested has cross-correlated acceptably. Used for filling MATCH matrix.

M2HIGH - Highest number of sequences with which any one sequence has cross-correlated acceptably. Used for MATCH matrix output. (This is not the maximum number of cross-correlation matches existing. Correlation is checked, and matches stored but once, commencing with the first sequence in the AUTO-C set and working up. Thus M2HIGH does not include matches between the sequence being tested and previous sequences in the AUTO-C set.)

Other variables are defined under "Arrays" and "Commcn."

Output

(1) The UW and CTUW sequences from the AUTO-C set which are being cross-correlated are output in decimal format, together with an index number which denotes the order in which the sequences are tested.

(2) The matching matrix (MATCH) is output in two-dimensional form. The elements of MATCH are the index numbers corresponding to the AUTO-C set of sequences. There is one row for each AUTO-C UW (See Section IV.B). The first element of a row is the index number of the UW, and the remainder of the row contains (higher) index numbers of the UW's and CTUW's with which it matches.

Program

```
C FILL MATCH WITH ZEROS
      DO 103 I=1,IDIM1
      DO 103 J=1,IDIM2
103   MATCH(I,J)=0
C PACK MCROSS
      DO 104 I=1,NUW
C OUTPUT THE AUTO-C SET ELEMENTS AND CORRESPONDING INDICES
104   MCROSS(NUW+I)=GCTUW(I)
      WRITE(6,610)
      WRITE(6,611) (I,MCROSS(I),I=1,NAUTO)
C INITIALIZATION
      L=1
      M2=2
      M2HIGH=2
C SELECT NEXT UW FROM AUTO-C SET
105   UW=MCROSS(L)
C DIMENSION OVERFLOW TEST
      IF(L.GT.IDIM1) GO TO 155
C STORE INDEX NUMBER OF UW
      MTEMP(1)=L
C SET INDEX OF FIRST AUTO-C ELEMENT BEING CHECKED AGAINST UW
      M=L+1
C CHECK CROSS-CORRELATION WITH ZERO SHIFT BETWEEN UW AND
C SUW.  THE IN-LINE SEGMENT IS IDENTICAL IN PURPOSE TO THE
C FIRST IN-LINE ROUTINE OF PREVIOUS PROGRAM SEGMENT
110   ICOUNT=0
      I=0
      JFLAG=0
      SUW=MCROSS(M)
S     LDA N
S     ADD =077677777
S     RCH 070100,1
S     LDA UW
S     EOR SUW
S     SHIFT 01001
S     SKE =040000000
S     MPC ICOUNT
S     BRX $-3,1
C DOES PAIR FAIL TEST AT I=0?
      IF(ICOUNT.GE.N-IEPS) GO TO 117
C COMMENCE LOOP FOR COMPUTING RIGHT-SHIFTED CROSS-
C CORRELATION.  THE IN-LINE SEGMENT IS IDENTICAL IN PURPOSE
C TO THE ONE ABOVE.
115   I=I+1
      ICOUNT=0
S     LDA N
S     SUB I
S     ADD =077677777
S     RCH 070100,1
S     LDA SUW
S     SHIFT C21001
S     STA SUW
S     EOR UW
S     SHIFT 01001
S     SKE =040000000
S     MPC ICOUNT
S     BRX $-3,1
C ARE WE ON DISTRIBUTION TAIL?
      IF(I.GE.N-IEPS) GO TO 140
C DOES PAIR PASS TEST AT STEP I?
      IF(ICOUNT.LT.N-IEPS-I) GO TO 115
C INCREMENT INDEX
117   M=M+1
```

```
C HAVE WE CHECKED UW AGAINST ALL HIGHER ORDER SEQUENCES?
      IF(M.LE.NAUTO) GO TO 110
C FINISHED WITH UW. STORE MATCHES.
120   M2=M2-1
      DO 125 K=1,M2
      MATCH(L,K)=MTEMP(K)
125   MTEMP(K)=0
C STORE NUMBER OF UW MATCHES IN FIRST UNUSED ROW ELEMENT
      MATCH(L,IDIM2)=M2
C IS M2 HIGHER THAN FOR ANY PREVIOUS UW?
      IF(M2.GT.M2HIGH) M2HIGH=M2
      M2=2
C TIME TO GET NEW UW.
      L=I+1
C ARE WE FINISHED?
      IF(L.LE.NUW) GO TO 105
C CROSS-C SORT COMPLETE.  OUTPUT MATCH.
135   WRITE(6,655)
      L=L-1
      DO 137 I=1,L
137   WRITE(6,660) (MATCH(I,J),J=1,M2HIGH)
      GO TO 300
C
C GO TO MATCHING ROUTINE
C
C DOES PAIR PASS ZERO TEST AT STEP I?
140   IF(ICOUNT.GT.0) GO TO 117
      JFLAG=JFLAG+1
C ARE WE FINISHED WITH RIGHT-SHIFT?
      IF(JFLAG.LT.IEPS) GO TO 115
      I=0
      JFLAG=0
      SUW=MCROSS(M)
C START LOOP FOR COMPUTING LEFT-SHIFTED CROSS-CORRELATION.
C THE IN-LINE SEGMENT INITIALIZES N-I AND I COUNTERS, LOADS
C SUW INTO A-REGISTER, SHIFTS SUW LEFT ONE BIT, STORES THE
C RESULT FOR LATER USE, COMPUTES MOD-2 SUM OF UW AND SUW,
C SHIFTS THE MOD-2 SUM RIGHT I BITS SO THAT THE N BITS OF
C INTEREST ARE RIGHT-JUSTIFIED IN THE A-REGISTER, COUNTS
C NUMBER OF ZEROS IN FIRST N-I POSITIONS (FROM RIGHT) OF
C THE MOD-2 SUM.
145   I=I+1
      ICOUNT=0
S     LDA N
S     SUB I
S     ADD =077677777
S     RCH 070100,1
S     LDA I
S     ADD =077677777
S     RCH 070100,2
S     LDA SUW
S     SHIFT 025001
S     STA SUW
S     ECR UW
S     SHIFT 01001
S     BRX $-1,2
S     SHIFT 01001
S     SKB =040000000
S     MPC ICOUNT
S     BRX $-3,1
      IF(I.GE.N-IEPS) GO TO 150
      IF(ICOUNT.LT.N-IEPS-I) GO TO 145
      GO TO 117
150   IF(ICOUNT.GT.0) GO TO 117
      JFLAG=JFLAG+1
      IF(JFLAG.LT.IEPS) GO TO 145
C HAVE A GOOD MATCH. STORE IN MTEMP
      MTEMP(M2)=M
      M2=M2+1
C DIMENSION OVERFLOW CHECK
      IF(M2.LT.IDIM2-1) GO TO 117
      WRITE(6,665) L
```

```
      GO TO 120
155   WRITE(6,670)
      GO TO 135
C
610   FORMAT('1','AUTOCORRELATION WORDS FROM ABOVE WHICH',
     1' ARE BEING CHECKED FOR CROSS-CORRELATION MATCHES'//)
611   FORMAT(6(1X,I4,'.',2X,I5,8X))
655   FORMAT('0','GOOD CROSS-CORRELATION PAIRS. THE NUMBER',
     1' LISTED IS THE SUBSCRIPT OF THE CORRESPONDING GOOD',
     2' AUTOCORRELATION WORD.'//)
660   FORMAT('0',10(1X,2016/))
665   FORMAT('0','OVERFLOW OF DIMENSION IDIM2 ATTEMPTED',
     1' WHEN L=',3I)
670   FORMAT('0','PROGRAM TERMINATED TO PREVENT OVERFLOW',
     1' OF DIMENSION IDIM1')
```

Matching Routine

Variables

MOST - Length of largest set found at any given point in search. Smaller sets, when found, are not output.

LTEST - Sets the last row element which must be looked at based on current value of MOST.

MAT1 - An element from the matrix row which has MAT2 as the leading element.

MAT2 - The last element of the current set being formed.

MAT3 - An element from the matrix row which has one of the set members as a leading element. Once it is known that a potential addition matches with the first and last elements of the set, MAT3 is used to check if it matches with the other elements as well.

Other variables are defined under "Arrays" and "Common."

Output

Match sets are output one line at a time in decimal format with the autocorrelation index preceding each element of the set.

Program

```
C SETS ARE FORMED BY FINDING ALL THOSE THAT HAVE THE I'TH
C ROW LEADING ELEMENT AS THE LEADING ELEMENT OF THE SET.
C IT IS KNOWN THAT ALL ELEMENTS OF A ROW MATCH WITH THE
C FIRST AND IT IS NECESSARY TO DETERMINE WHICH OF THESE
C IN TURN MATCH WITH ONE ANOTHER.  IF A ROW ELEMENT IS
C GREATER THAN NUW, IT COMES FROM THE CTUW PORTION OF THE
C AUTO-C SET AND WILL NOT APPEAR AS A ROW LEADING ELEMENT.
C FOR THIS CASE, THE CORRESPONDING UW ROW IS USED TO
C DETERMINE WHAT FURTHER MATCHES EXIST.
C
C
C INITIALIZE
300    WRITE(6,700)
       MOST=3
       I=1
       M=2
C START LOOKING FOR SETS WHICH HAVE AUTO-C NO. 1 AS LEADING
C ELEMENT
305    K=2
C COMPUTE LTEST
310    IF(MATCH(I,K).GT.NUW) ,LTEST=MATCH(MATCH(I,K)-NUW,
       1IDIM2)+M+1-MOST; GO TO 312
       LTEST=MATCH(MATCH(I,K),IDIM2)+M+1-MOST
C GO TO NEXT ROW
312    IF(MATCH(I,K).GT.0) GO TO 315
       I=I+1
C ARE WE FINISHED?
       IF(I.GT.NUW) STOP
       GO TO 310
C IS NEXT ELEMENT IN ROW A ZERO?  IF SO, TIME TO GO TO
C NEXT ROW.
315    IF(MATCH(I,K+1).GT.0) GO TO 320
       I=I+1
       IF(I.GT.NUW) STOP
       GO TO 305
320    L=1
       J=K+1
C IS MATRIX ELEMENT A 'CTUW'?
325    IF(MATCH(I,K).GT.NUW) GO TO 415
C START LOOKING FOR NEXT ADDITION TO MATCH SET
327    L=L+1
       IF(L.GT.LTEST) GO TO 372
       MAT1=MATCH(MATCH(I,K),L)
       IF(MAT1.EQ.0) GO TO 370
330    MAT2=MATCH(I,J)
       IF(MAT2.LE.0) GO TO 370
       IF(MAT2.LE.MAT1) GO TO 335
       GO TO 327
C DO WE HAVE A POTENTIAL ADDITION TO SET?
335    IF(MAT1.EQ.MAT2) GO TO 340
       J=J+1
       GO TO 330
C IS THE CURRENT SET LENGTH EQUAL TO TWO?  IF SO, TAKE THE
C NEW ADDITION WITHOUT QUESTION.
340    IF(M.EQ.2) GO TO 365
C MUST CHECK IF POTENTIAL NEW ADDITION MATCHES WITH OTHER
C ELEMENTS ALREADY IN SET
       M1=M-1
       DO 350 MM=2,M1
       IF(MTEMP(MM).GT.NUW) GO TO 352
       LL=2
345    MAT3=MATCH(MTEMP(MM),LL)
C IF FOLLOWING TRUE, NEW ADDITION NO GOOD
       IF(MAT3.EQ.0.OR.MAT3.GT.MAT2) GO TO 325
       IF(MAT3.EQ.MAT2) GO TO 350
       LL=LL+1
       GO TO 345
350    CONTINUE
```

```
C HAVE NEW ADDITION TO SET
      GO TO 355
352   MAT2=MAT2-NUW
      DO 354 MM1=MM,M1
      LL=2
353   MAT3=MATCH(MTEMP(MM1)-NUW,LL)
      IF(MAT3.EQ.0.OR.MAT3.GT.MAT2) GO TO 325
      IF(MAT3.EQ.MAT2) GO TO 354
      LL=LL+1
      GO TO 353
354   CONTINUE
      MAT2=MAT2+NUW
C STORE NEW ADDITION AND SET POINTER
355   M=M+1
      MTEMP(M)=MAT2
      INCR(M)=J
C START LOOKING FOR SEQUENCES WHICH MATCH WITH FIRST AND
C (NEW) LAST ELEMENT OF SET.
      K=J
      IF(MATCH(I,K).GT.NUW),LTEST=MATCH(MATCH(I,K)-NUW,
     1IDIM2)+M+1-MOST; GO TO 320
      LTEST=MATCH(MATCH(I,K),IDIM2)+M+1-MOST
      GO TO 320
C STORE FIRST TWO ELEMENTS OF 2-ELEMENT SET AND SET
C POINTERS.  THEN GO TO POINT WHERE NEW ELEMENT IS ADDED
C TO SET
365   MTEMP(1)=I
      MTEMP(2)=MATCH(I,K)
      INCR(1)=I
      INCR(2)=K
      GO TO 355
C
C HAVE EXHAUSTED POSSIBILITIES FOR ADDITIONS TO CURRENT SET
C
C IS SET LENGTH OF INTEREST? IF SO, OUTPUT;  IN ANY CASE,
C BACK UP TO NEXT-TO-LAST ELEMENT OF SET AND LOOK FOR
C FURTHER POTENTIAL ADDITIONS.
370   IF(M.GE.MOST) GO TO 375
372   IF(M.EQ.2) GO TO 405
      GO TO 380
375   MOST=M
      WRITE(6,705) (MTEMP(M1),MCROSS(MTEMP(M1)),M1=1,MOST)
380   K=INCR(M-1)
      J=INCR(M)+1
      L=1
      IF(MATCH(I,K).GT.NUW) GO TO 450
      MAT1=MATCH(I,K)
      MAT2=MATCH(I,INCR(M))
385   L=L+1
      IF(MATCH(MAT1,L).LT.MAT2) GO TO 385
      M=M-1
      LTEST=MATCH(MATCH(I,K),IDIM2)+M+1-MOST
      GO TO 327
405   K=K+1
      IF(MATCH(I,K).GT.NUW),LTEST=MATCH(MATCH(I,K)-NUW,
     1IDIM2)+M+1-MOST; GO TO 315
      LTEST=MATCH(MATCH(I,K),IDIM2)+M+1-MOST
      GO TO 315
C REMAINING STATEMENTS HANDLE CHECKS WHEN MATRIX ELEMENT IN
C QUESTION IS FROM CTUW AUTO-C SUBSET
415   MAT3=MATCH(I,K)-NUW
420   L=L+1
      IF(L.GT.LTEST) GO TO 372
      MAT1=MATCH(MAT3,L)
      IF(MAT1.EQ.0) GO TO 370
425   MAT2=MATCH(I,J)-NUW
      IF(MAT2.LE.0) GO TO 370
      IF(MAT2.LE.MAT1) GO TO 430
      GO TO 420
430   IF(MAT1.EQ.MAT2),MAT2=MAT2+NUW;GO TO 340
      J=J+1
      GO TO 425
```

```
450     MAT1=MATCH(I,K)-NUW
        MAT2=MATCH(I,INCR(M))-NUW
455     L=L+1
        IF(MATCH(MAT1,L).LT.MAT2) GO TO 455
        M=M-1
        LTEST=MATCH(MAT1,IDIM2)+M+1-MOST
        GO TO 415
C
700     FORMAT('1','GOOD CROSS-CORRELATION SETS'//)
705     FORMAT('0',5(1X,7(I4,')',1X,I6,5X)/))
        END
```

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